1985

An autopilot for course keeping and track following.

Vimuktananda, Sommart.

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

AN AUTOPILOT FOR COURSE KEEPING
AND
TRACK FOLLOWING

by

Sommart Vimuktananda
September 1985

Thesis Advisor: G.J. Thaler

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) An Autopilot for Course Keeping and Track Following	5. TYPE OF REPORT & PERIOD COVERED Master's Thesis September 1985
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Sommart Vimuktananda	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey,California 93943	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey,California 93943	12. REPORT DATE September,1985
	13. NUMBER OF PAGES 89
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Course Keeping,Track Following,Parole Program
Stabilizing,Compensation,Trajectory

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Computer control of ship steering provides track following as well as course keeping.The desired track is stored in the computer,and the position of the ship(as provided by a satellite navigation system) is compared with track coordinates.A heading correction is calculated continuously and used to up date the course command.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S N 0102- LF- 014- 6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

An Autopilot for Course Keeping and Track Following

by

Sommart Vimuktananda
Lieutenant, Royal Thai Navy
B.S., Royal Thai Naval Academy, 1974

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1985

ABSTRACT

Computer control of ship steering provides track following as well as course keeping. The desired track is stored in the computer,and the position of the ship(as provided by a satellite navigation system) is compared with track coordinates.A heading correction is calculated continuously and used to up date the course command.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The basic reasons for using an autopilot on a ship are to reduce the number of operator controls,minimize rudder orders for Course-keeping,and reduce the traveling time between destinations.

In the past autopilots were used extensively to maintain a given course. They work well but most autopilots are for course control only,the effect of an ocean current and/or wind during travel are not considered. When a disturbance is applied,the ship follows the desired course but does not follow the given track without correction. This problem has been studied [Ref. 1]. The correction needed to compensate for errors due to the effect of a current and/or wind were found.

The purpose of this thesis is to develop a procedure to compensate for the error in position and reduce it as much as possible, then the autopilot can be used for both Course-keeping and Track following.

Today,many ships have computers on board. The computer can be used to solve the problem of Track following. First,the desired trajectories are stored in the computer. When the computer receives measured X and Y positions the computer will provide the desired position with respect to X and Y and compare with the actual position.An error signal is obtained from trajectory information,and can be used to drive the ship close to the desired trajectory.

Actual position must be provided by the navigation system. The navigation system used in the Track following autopilot must be accurate,must give continuous information about the position of the ship,and the system must be useable everywhere in the world. It is felt that the NAVSTAR/GLOBAL POSITIONING SYSTEM can be used.

The NAVSTAR/GLOBAL POSITIONING SYSTEM(GPS),currently being developed by the Department of Defense,is a satellite based navigation system that will provide the user with extremely accurate three-dimensional position,velocity and time information on a 24-hour basis and in all weather conditions at any point on the earth.The user position is determined by measuring its range to four satellites.For more details refer to [Refs. 2,3].

II. COURSE-KEEPING

A. THE PRIMARY TRANSFER FUNCTION OF THE SYSTEM

The equations of motion by Davidson [Ref. 4] are:

$$m_2\psi + c_\ell\psi - m\Omega = c_\lambda\delta$$

$$n\Omega + c_\kappa\Omega - c_m\psi = c_\mu\delta$$

where $\Omega(s) = (\ell/V)\theta$

θ = turning angular velocity ;

V = ship speed;

ψ = drift angle ;

δ = helm angle ;

ℓ = ship length ;

denotes $d/ds = (\ell/V)d/dt$, $s = (V/\ell)t$

$m = (m_1 - c_f)$

m_1, m_2, n = coefficient of inertia ;

$c_\ell, c_\kappa, c_m, c_f$ = coefficient of resistance ;

c_μ, c_λ = coefficient of rudder force.

The former equation is the equation of lateral translation and the latter is the equation of turning angular motion.

Then rewriting the equations of motion in terms of time and taking the Laplace transform,we obtain the turning rate of the ship in steering [Ref. 5] is:

$$\dot{\theta}(s) = \frac{K(1+T_3 s)}{(1+T_1 s)(1+T_2 s)}\delta(s) + \frac{\{T_1 T_2 s + (T_1+T_2)\}\theta(0-) + T_1 T_2 \theta(0-)}{(1+T_1 s)(1+T_2 s)}$$

The first term corresponds to the ship motion excited by the steering,and the second corresponds to the memory of her motion at the beginning of the steering. Therefore,a relational function is:

$$\frac{\dot{\Theta}(s)}{\delta(s)} = \frac{K(1+T_3 s)}{(1+T_1 s)(1+T_2 s)} \qquad \text{-----(1)}$$

Equation(1) describes the response character of the ship to steering, which may be called the transfer function of the ship in steering.

In this study of automatic Course-keeping we will be working with a 200,000 DWT super-tanker of the following characteristics [Ref. 6],

length = 310.00 meters

breadth = 47.16 meters

Draft = 18.90 meters

Steering Quality indices.

T1 = -269.3 seconds

T2 = 9.3 seconds

T3 = 20.0 seconds

K = -0.0434 red/sec

Maximum Rudder Deflection = 30 degree

Maximum Rudder rate = 2.32 degrees/second

Substitute T1,T2,T3 and K in equation (1), we get:

$$\frac{\dot{\Theta}(s)}{\delta(s)} = \frac{-0.0434(1+20s)}{(1-269.3s)(1+9.3s)} \qquad \text{-----(2)}$$

B. STABILIZING THE SYSTEM

From equation(2),we see that one pole of the steering transfer function is in the right half plane,so the system is unstable. We have to stabilize the system by using an autopilot.

Assuming the autopilot has a gain G, Figure 2.1 is the block diagram of the system with an autopilot.

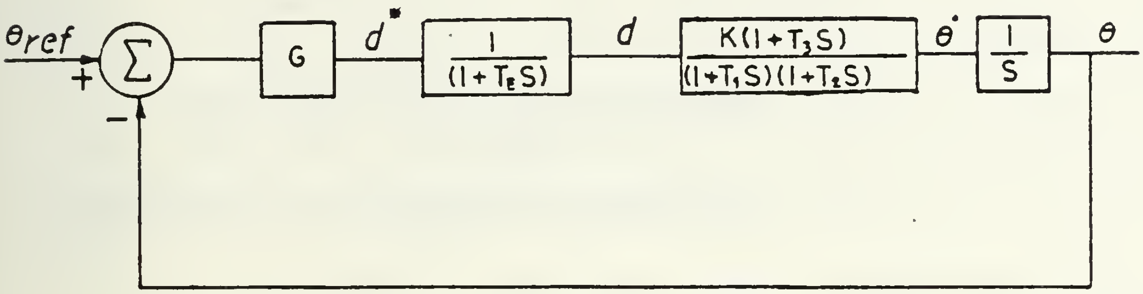

Figure 2.1 Block Diagram Of The System With An Autopilot.

The open loop transfer function for the system is

$$H(s) = \frac{GK(1+T_3 s)}{s(1+T_1 s)(1+T_2 s)(1+T_E s)}$$

Where $\frac{1}{(1+T_E s)}$ = the rudder servo transfer function.

From experience the value of T_E is 1 to 2 seconds and a good choice is 1.7 seconds,so the only parameter available to make the system stable is G.

To get the values of G for stability,we refer to the Routh criterion:

$$\frac{GK(1+T3s)}{s(1+T_E s)(1+T1s)(1+T2s)} = -1$$

$$s(1+T_E s)(1+T1s)(1+T2s)+GK(1+T3s) = 0$$

$$s(1+1.7s)(1-269.3s)(1+9.3s)-0.0434G(1+20s) = 0$$

$$s^4+0.692s^3+0.06s^2-(2.35\times10^{-4}-2.04\times10^{-4}G)s+1.02\times10^{-5}G = 0$$

s^4	1	0.06	$1.02\times10^{-5}G$

$$
\begin{array}{llll}
s^3 & 0.692 & -(2.35\times10^{-4}-2.04\times10^{-4}G) & 0 \\
s^2 & A & 1.02\times10^{-5}G & \\
s^1 & B & 0 & \\
s^0 & 1.02\times10^{-5}G & &
\end{array}
$$

Where

$$A = \frac{0.692\ 0.06+(2.35\times10^{-4}-2.04\times10^{-5}G)}{0.692}$$

$$B = \frac{-A(2.35\times10^{-4}-2.04\times10^{-4}G)-0.692\ 1.02\times10^{-5}G}{A}$$

To find the limits of G for stability, the values of A,B and $1.02\times10^{-5}G$ must be greater than zero.

In the s^2 row

$$A > 0$$

$$0.692\ 0.06+(2.35\times10^{-4}-2.04\times10^{-4}G) > 0$$

$$4.1755\times10^{-2}-2.04\times10^{-4}G > 0$$

$$G < 204.68$$

In the s^1 row

$$B > 0$$

$$-A(2.35\times10^{-4}-2.04\times10^{-4}G)-0.692\times1.02\times10^{-5}G > 0$$

After manipulation.

$$G^2 - 85G + 240 < 0$$

$$3 < G < 82$$

In the s^1 row

$$1.02\times10^{-5}G > 0$$

$$G > 0$$

So the condition of G for stability is

$$3 < G < 82$$

By using DSL/360, the system was simulated. The system was represented by the block diagram of Figure 2.1. The computer program for this system is contained in Appendix A.

Values of G were selected between 12 and 36,which are the ones with better time constants.

Figure 2.2 to Figure 2.9 are the computer outputs for different values of G. By comparing,we found that when G=24.2 (Figure 2.4,2.5) and G=30 (Figure 2.6,2.7) the settling time is almost the same and shorter, with less oscillation than for other values of G. When we compare the rudder angle for both values,we can see that when G=30 the rudder angle is larger so in this case G=24..2 is the best value.

Next we simulate a disturbance that produces the rate of turn caused by waves. For a large super tanker the rate of turn can easily reach as much as 0.2 or 0.3 deg./sec.(0.00349 or 0.00524 rad./sec.).

In this thesis the rate of turn 0.2 deg./sec. was used in the program. Figure 2.10 to Figure 2.17 are the computer outputs of this program. Figure 2.12,2.13 show that when G=24.2 the settling time and rudder angle are better than other values. Figure 2.18 is the Bode plot of this system which phase margin = 11.17 degrees and gain margin =-18.46 DB that are lower than normally used in practise.

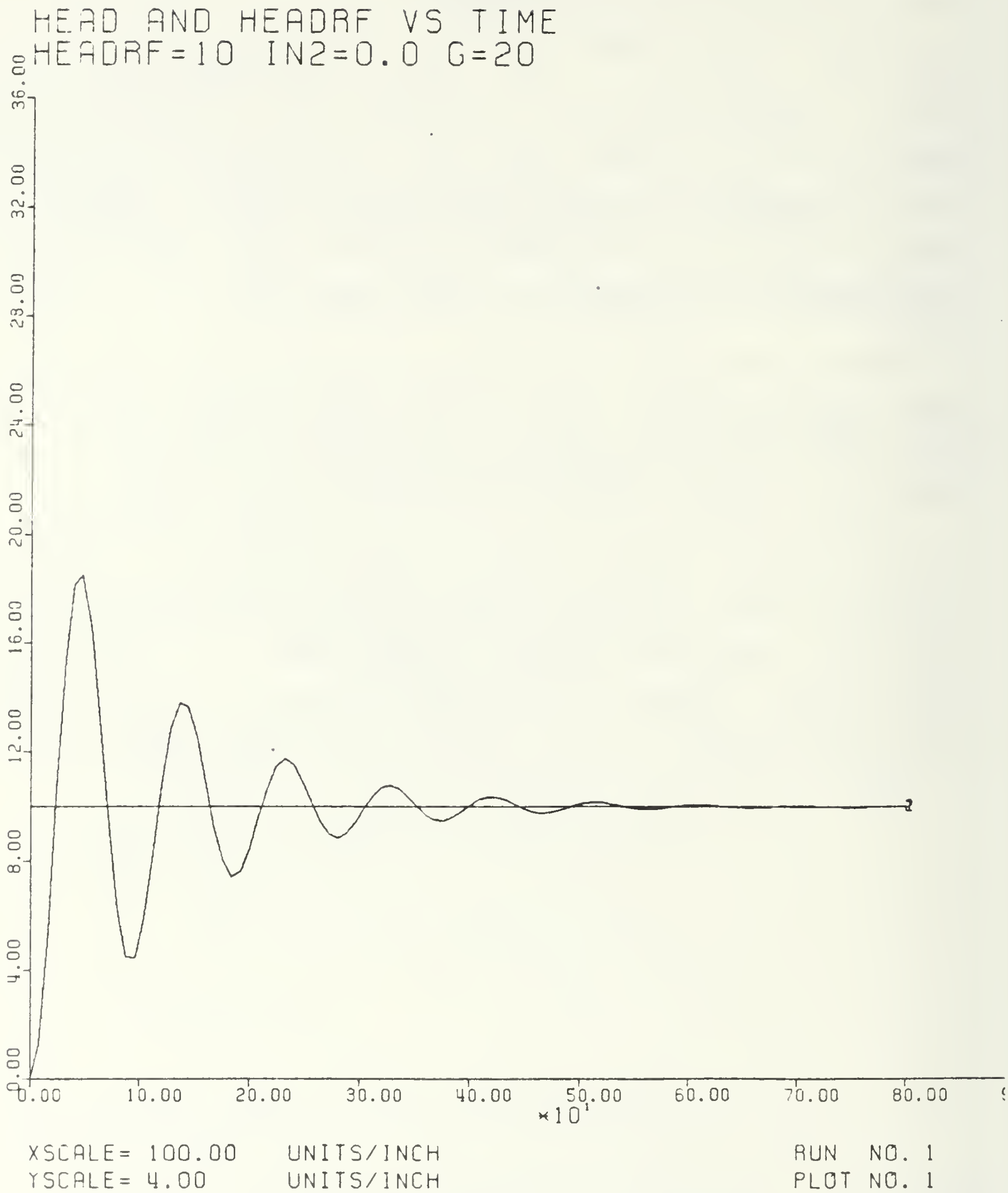

Figure 2.2 Ship Heading(1) and Heading Command(2) with G=20.

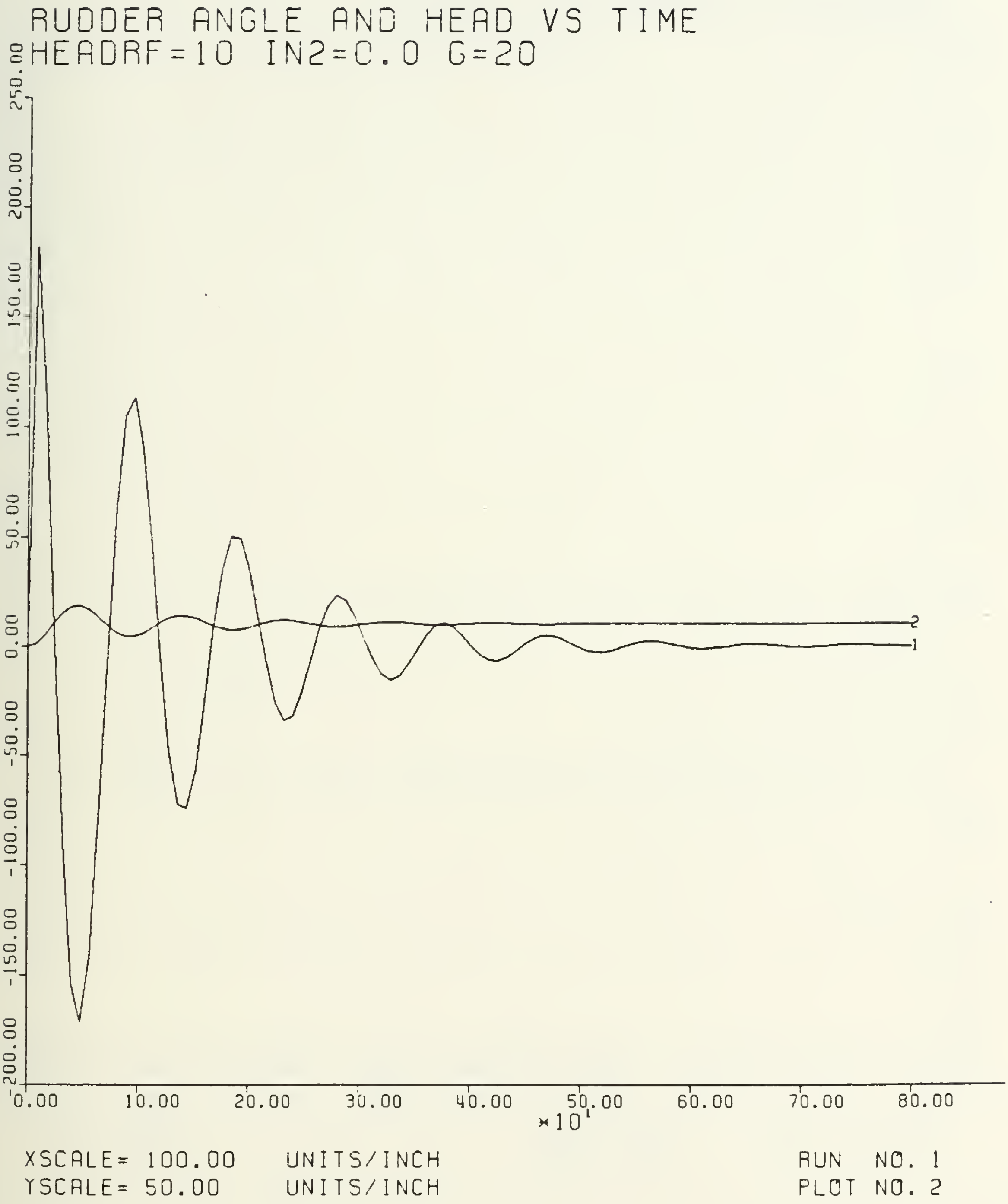

Figure 2.3 Rudder Angle(1) and Ship Heading(2) with G=20.

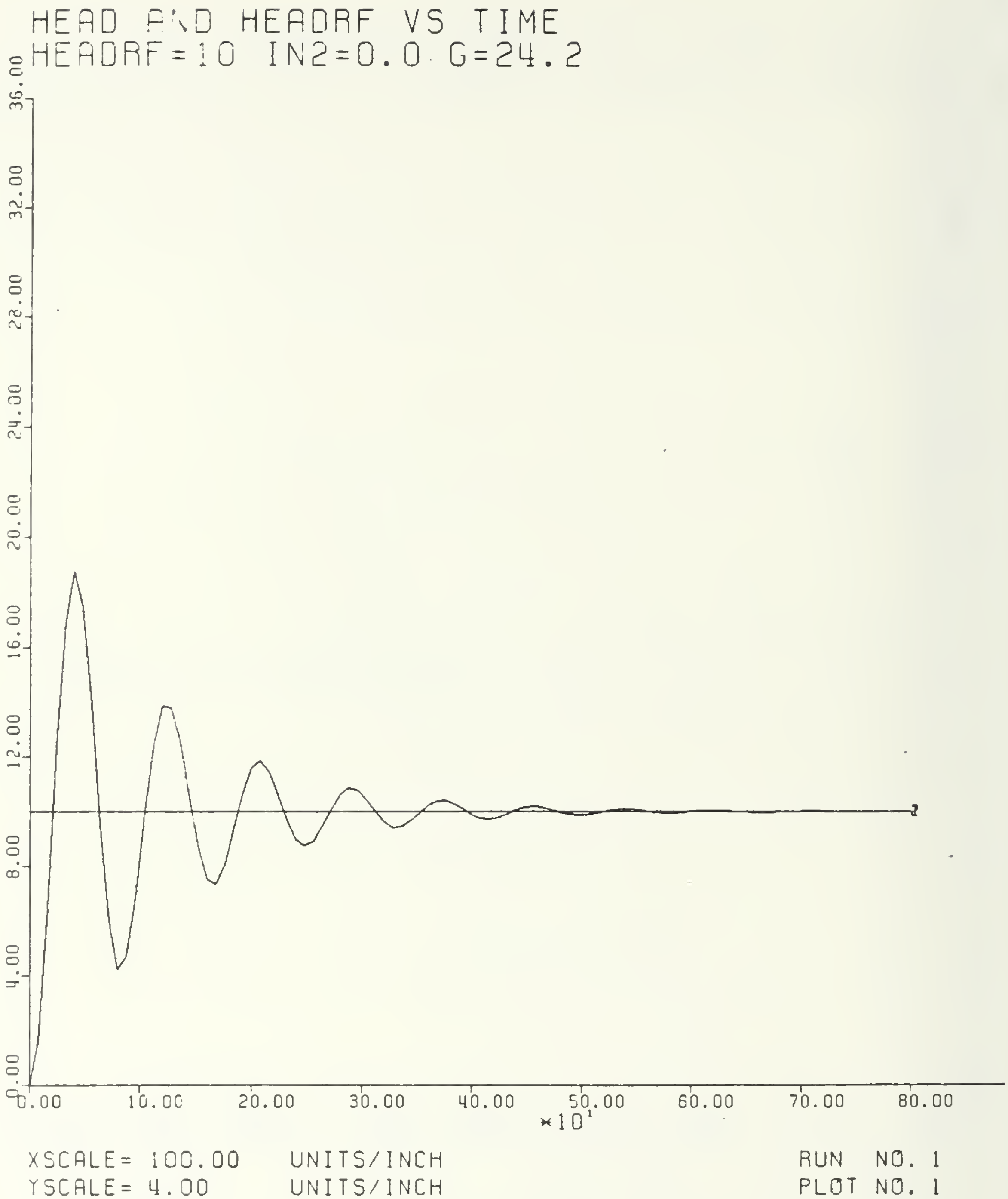

Figure 2.4 Ship Heading(1) and Heading Command(2) with G=24.2.

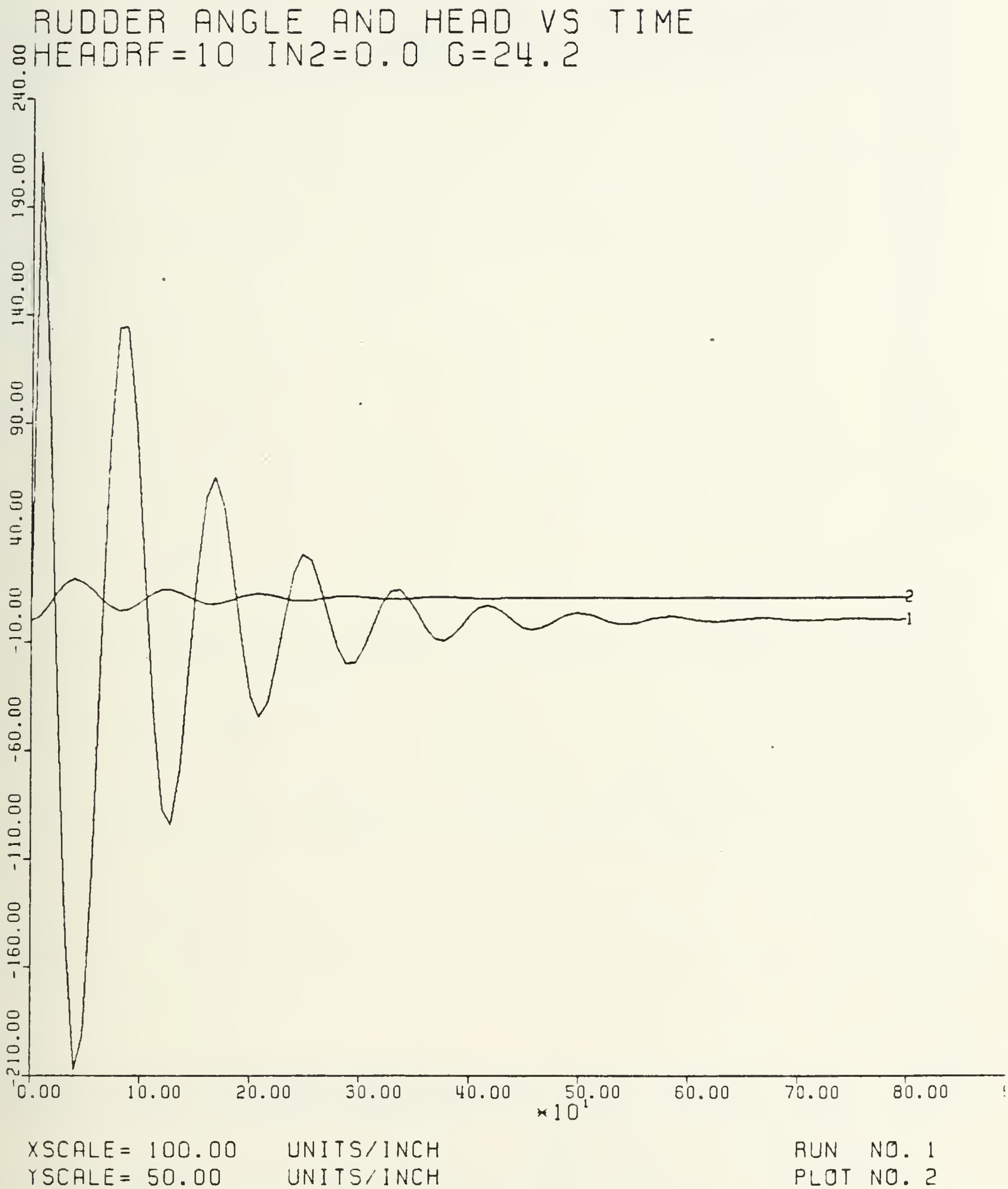

Figure 2.5 Rudder Angle(1) and Ship Heading(2) with G=24.2.

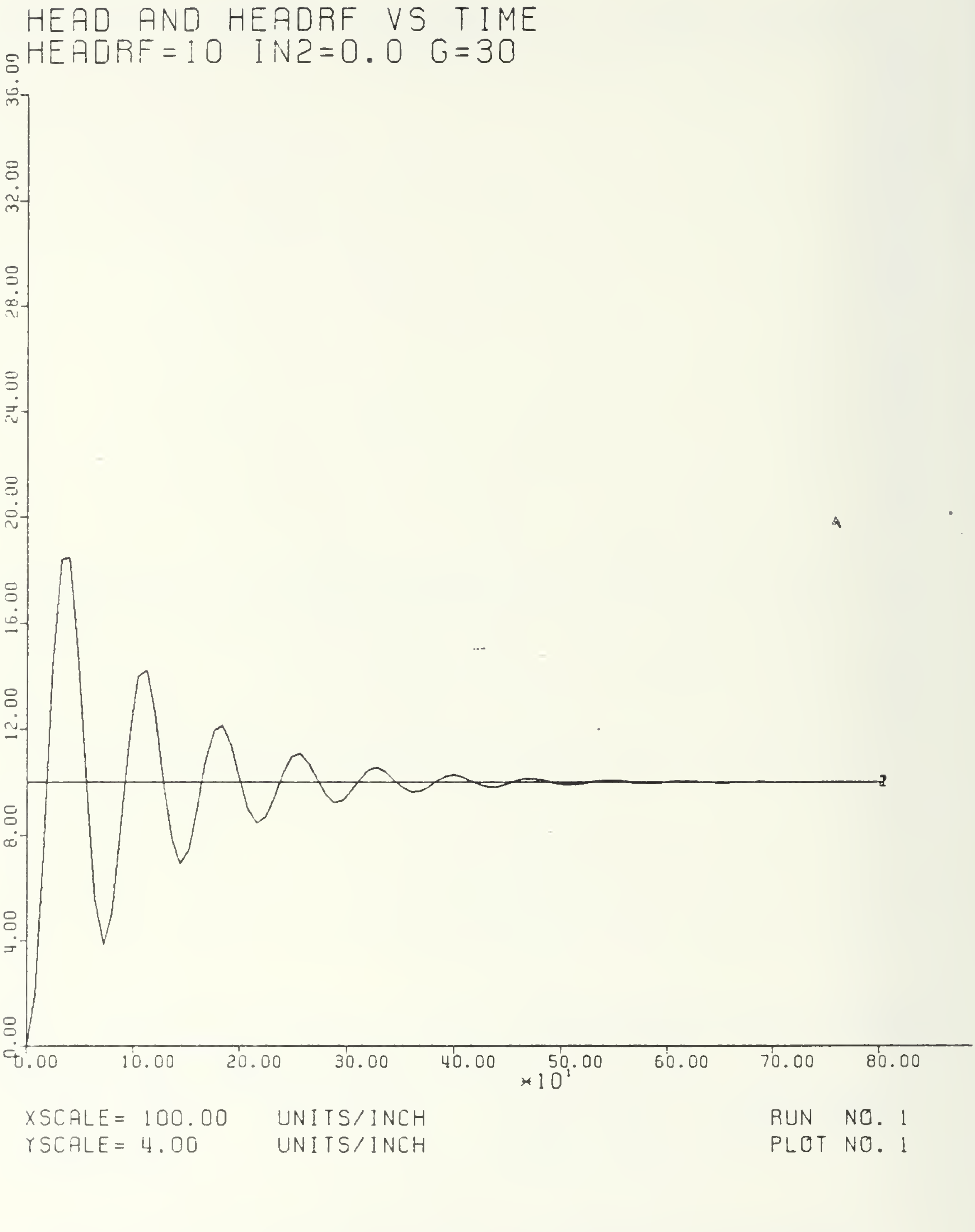

Figure 2.6 Ship Heading(1) and Heading Command(2) with G=30.

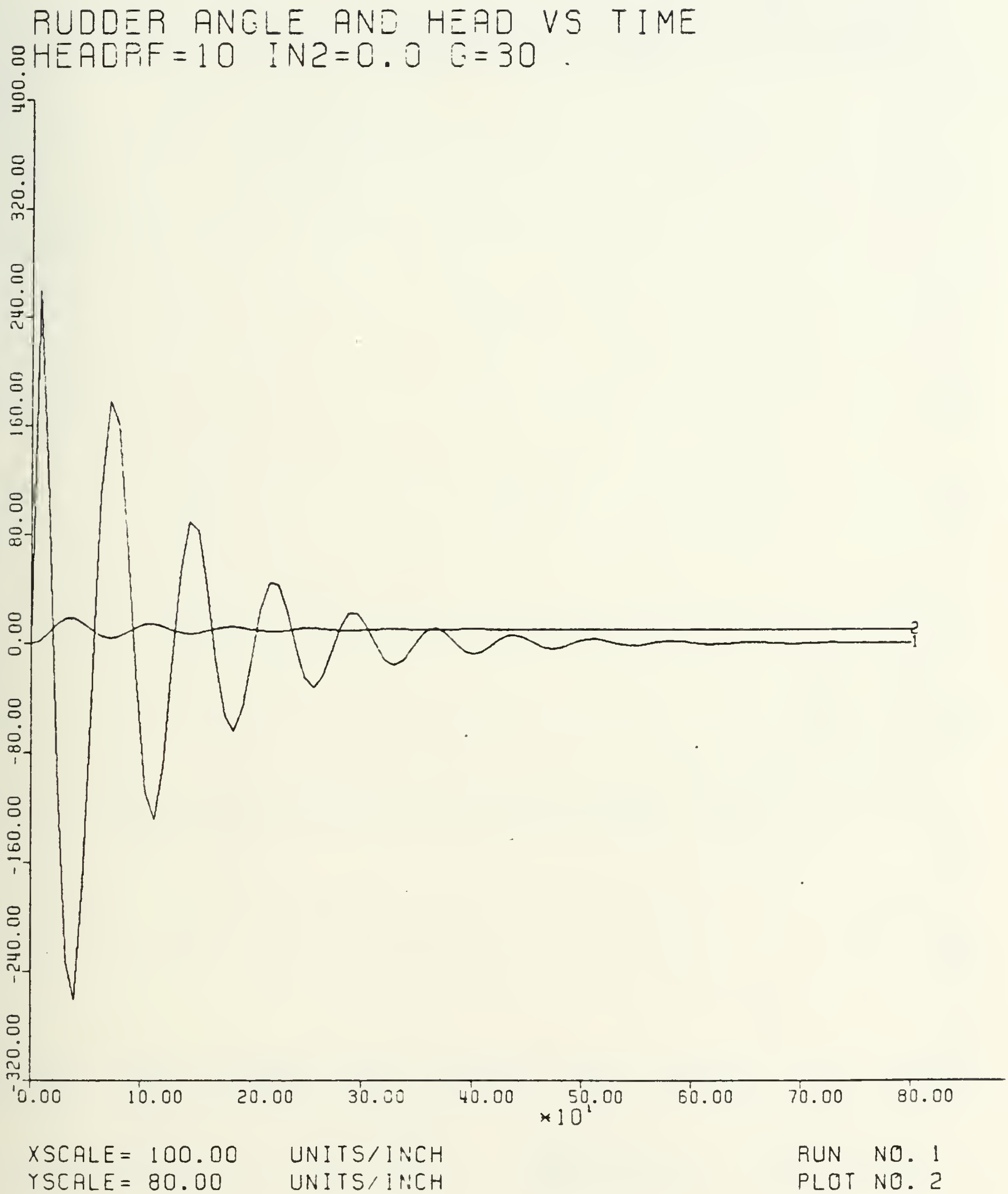

Figure 2.7 Rudder Angle(1) and Ship Heading(2) with G=30.

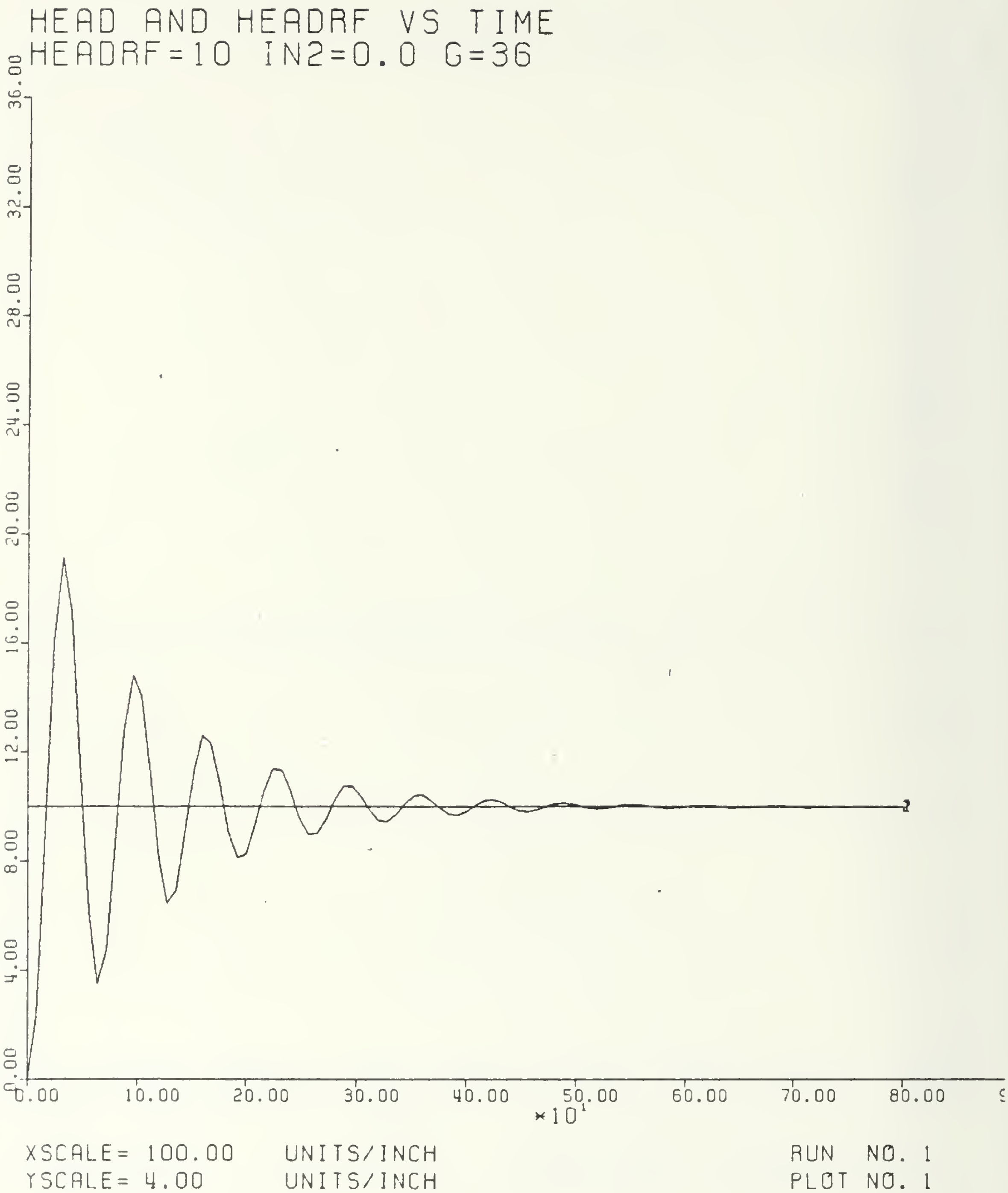

Figure 2.8 Ship Heading(1) and Heading Command(2) with G=36.

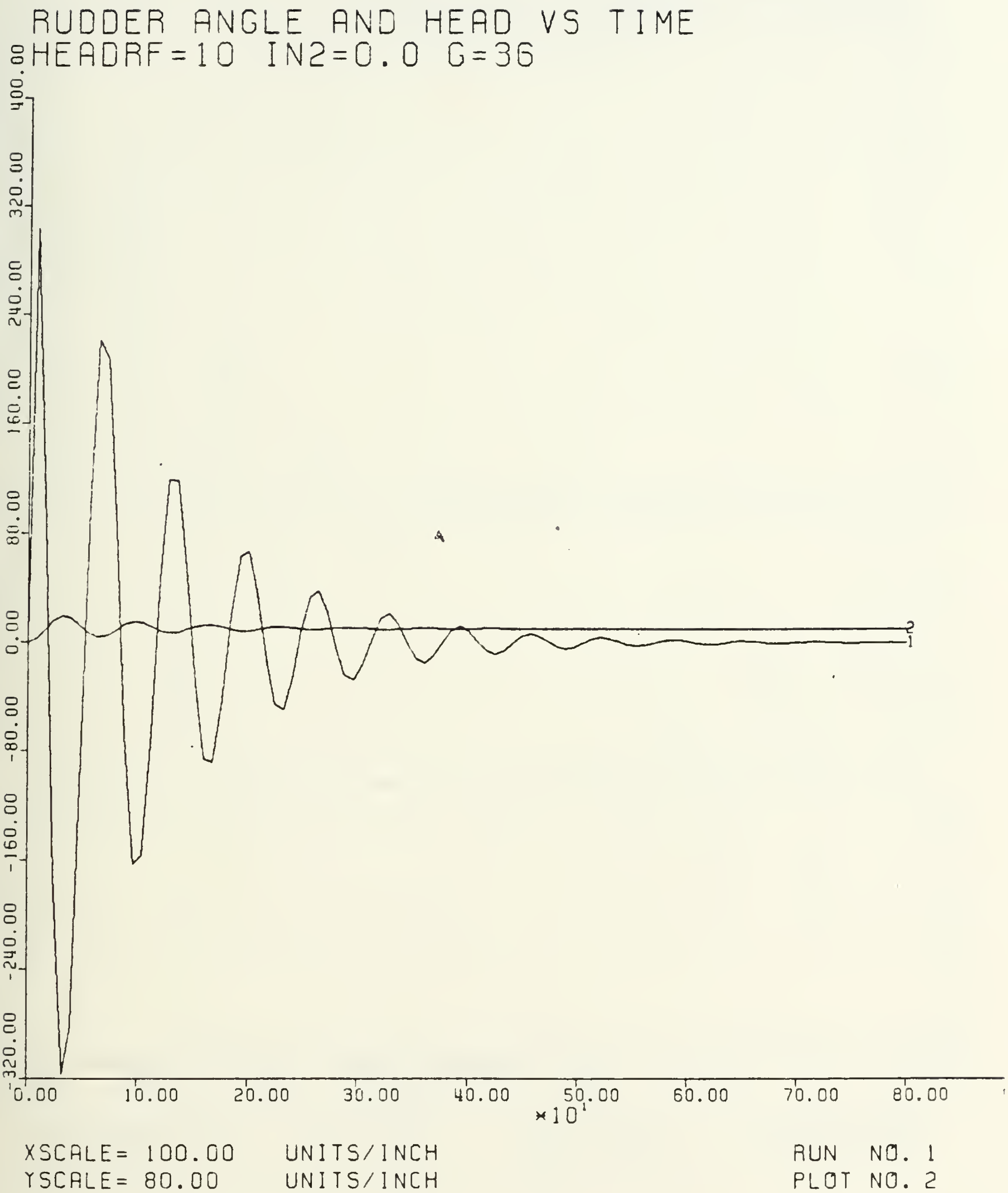

Figure 2.9 Rudder Angle(1) and Ship Heading(2) with G=36.

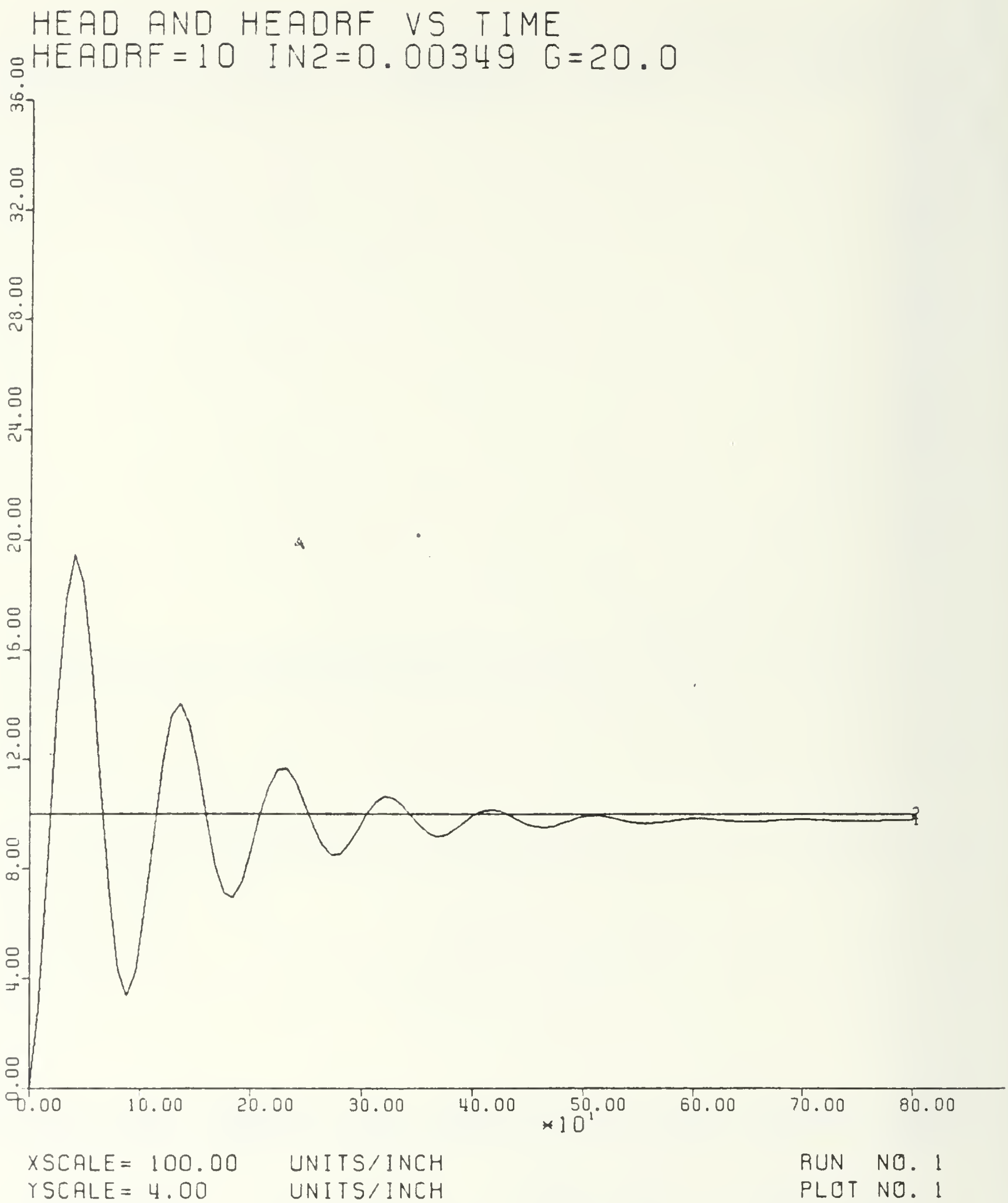

Figure 2.10 Ship Heading(1) and Heading Command(2) with Disturbance and G=20.

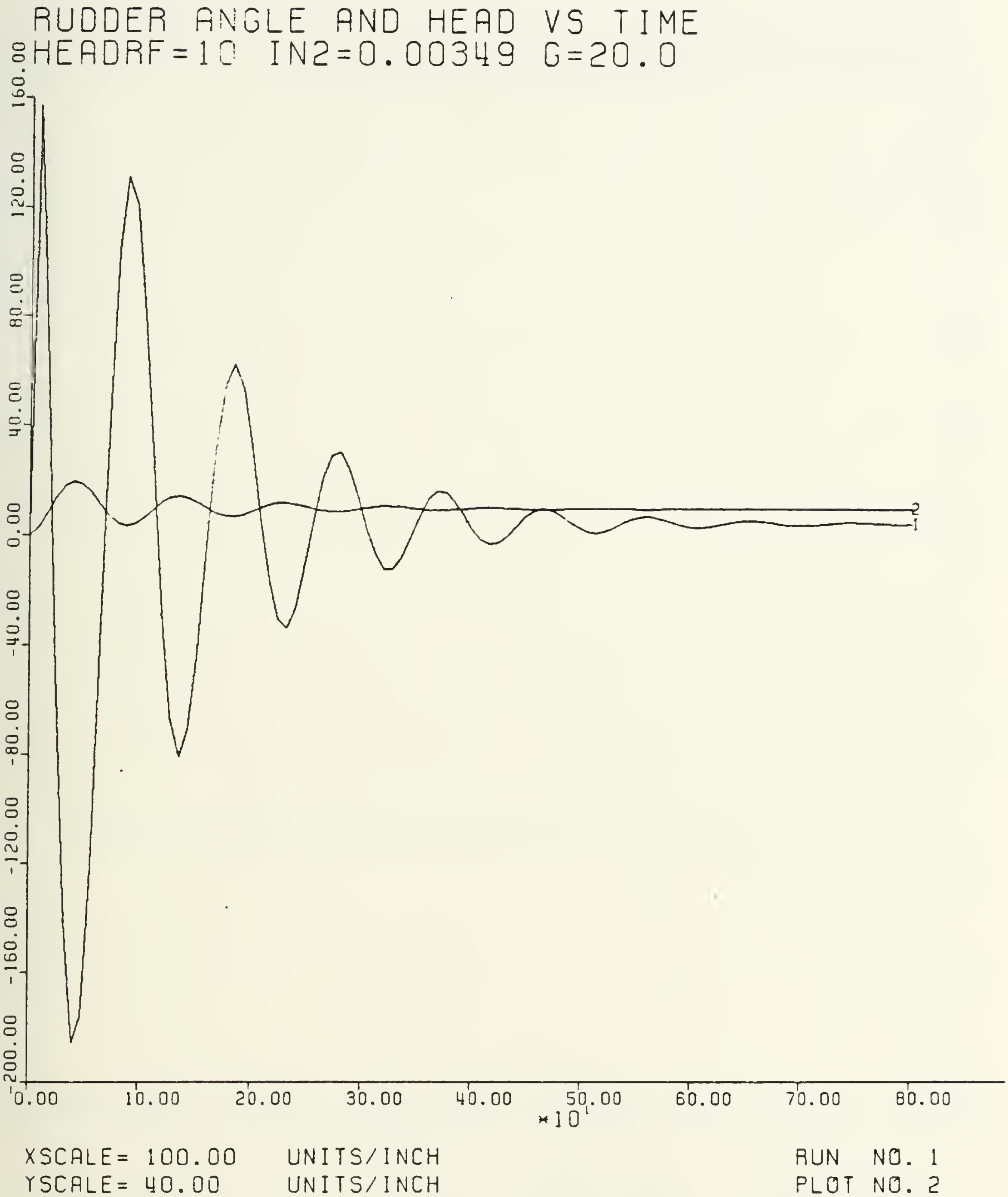

Figure 2.11 Rudder Angle(1) and Ship Heading(2) with Disturbance and G=20.

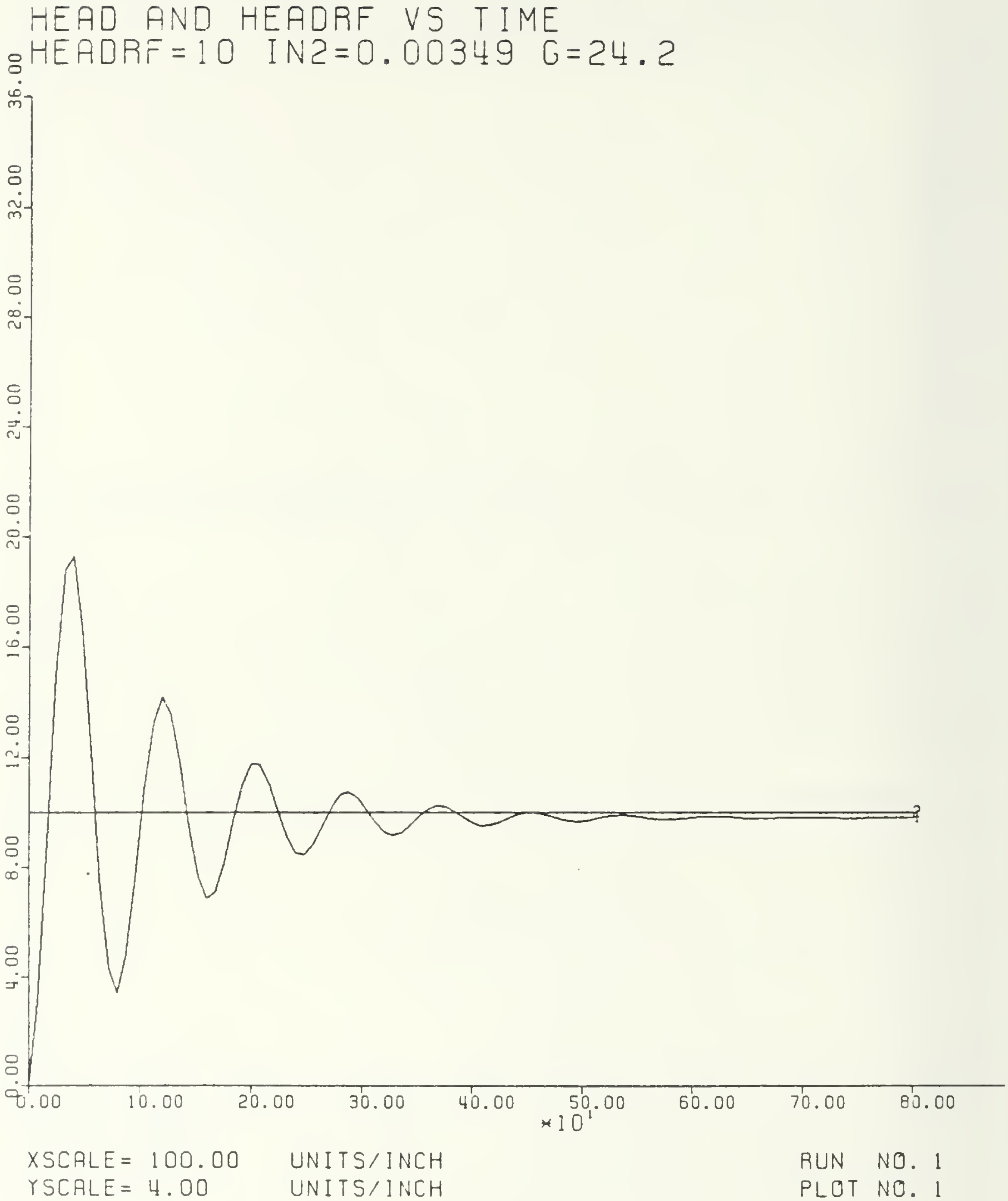

Figure 2.12 Ship Heading(1) and Heading Command(2) with Disturbance and G=24.2.

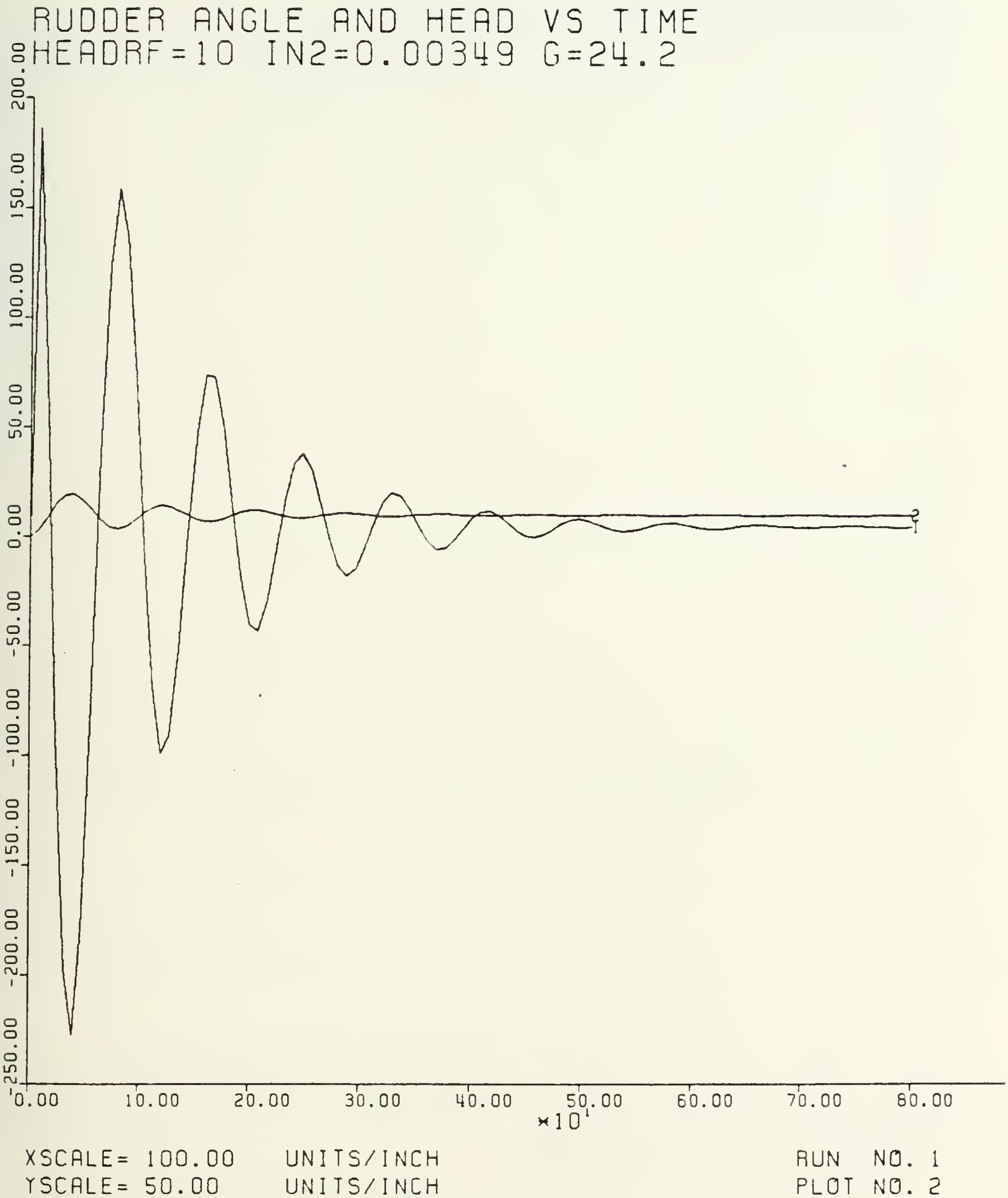

Figure 2.13 Rudder Angle(1) and Ship Heading(2) with Disturbance and G=24.2.

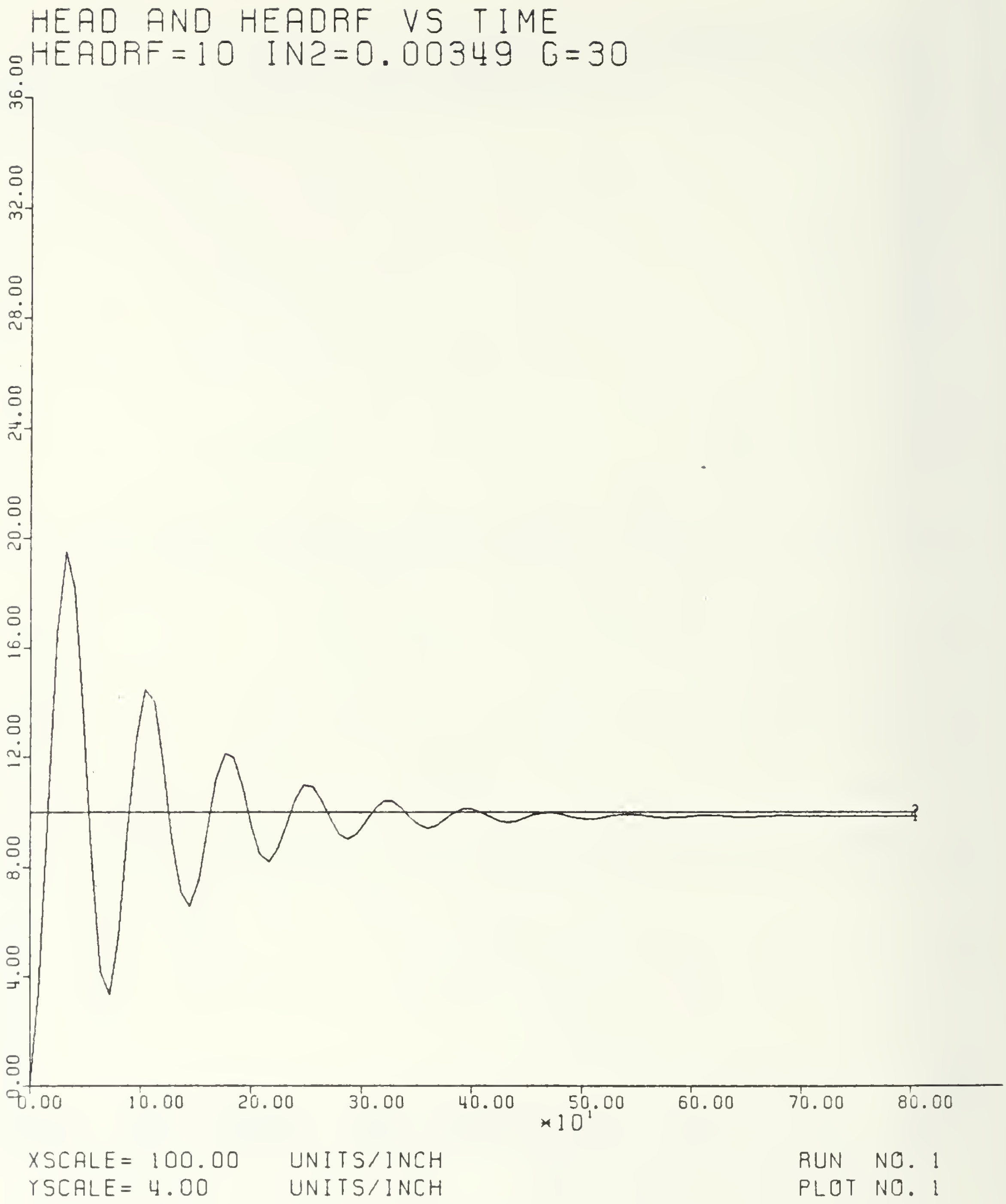

Figure 2.14 Ship Heading(1) and Heading Command(2) with Disturbance and G=30.

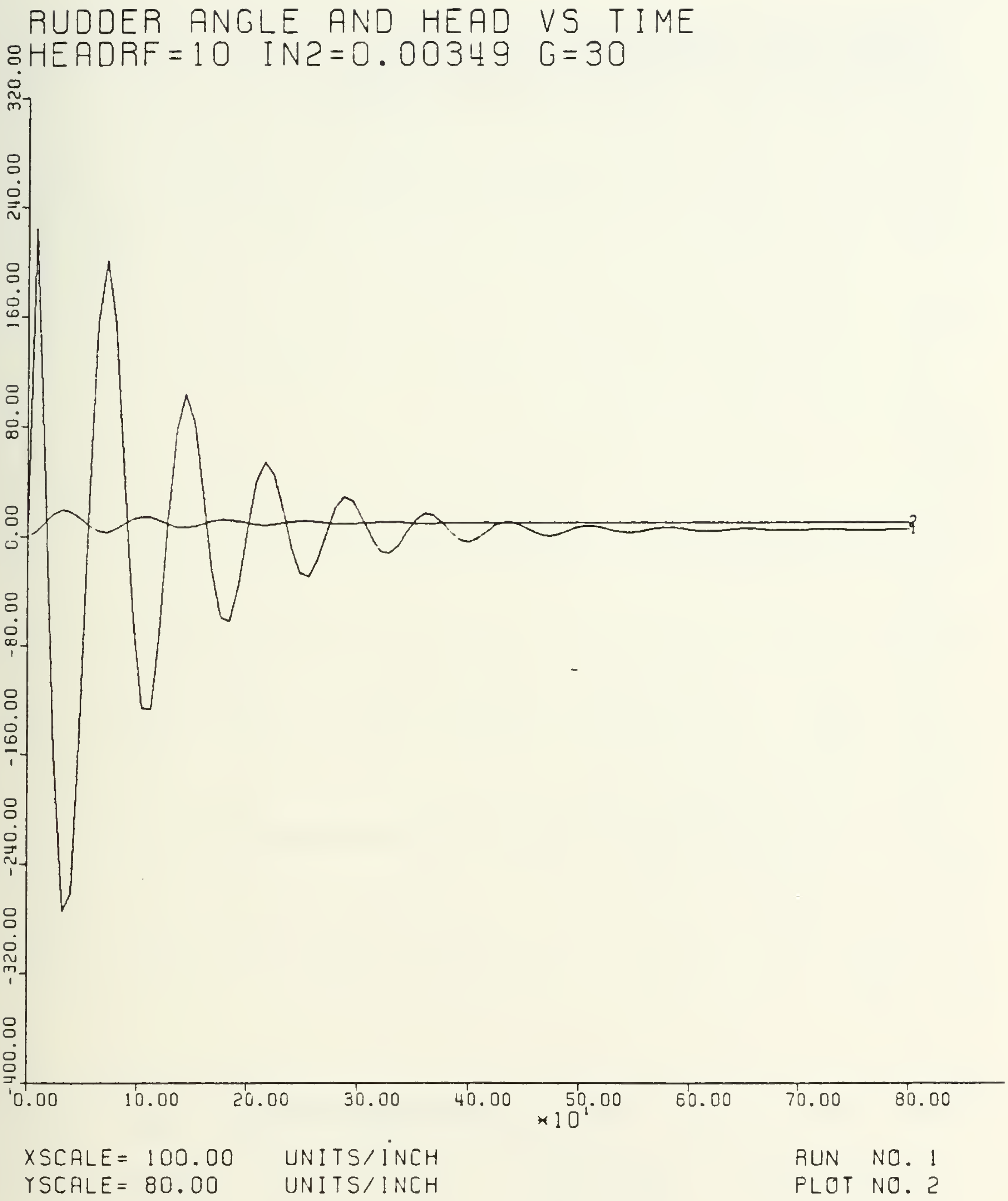

Figure 2.15 Rudder Angle(1) and Ship Heading(2) with Disturbance and G=30.

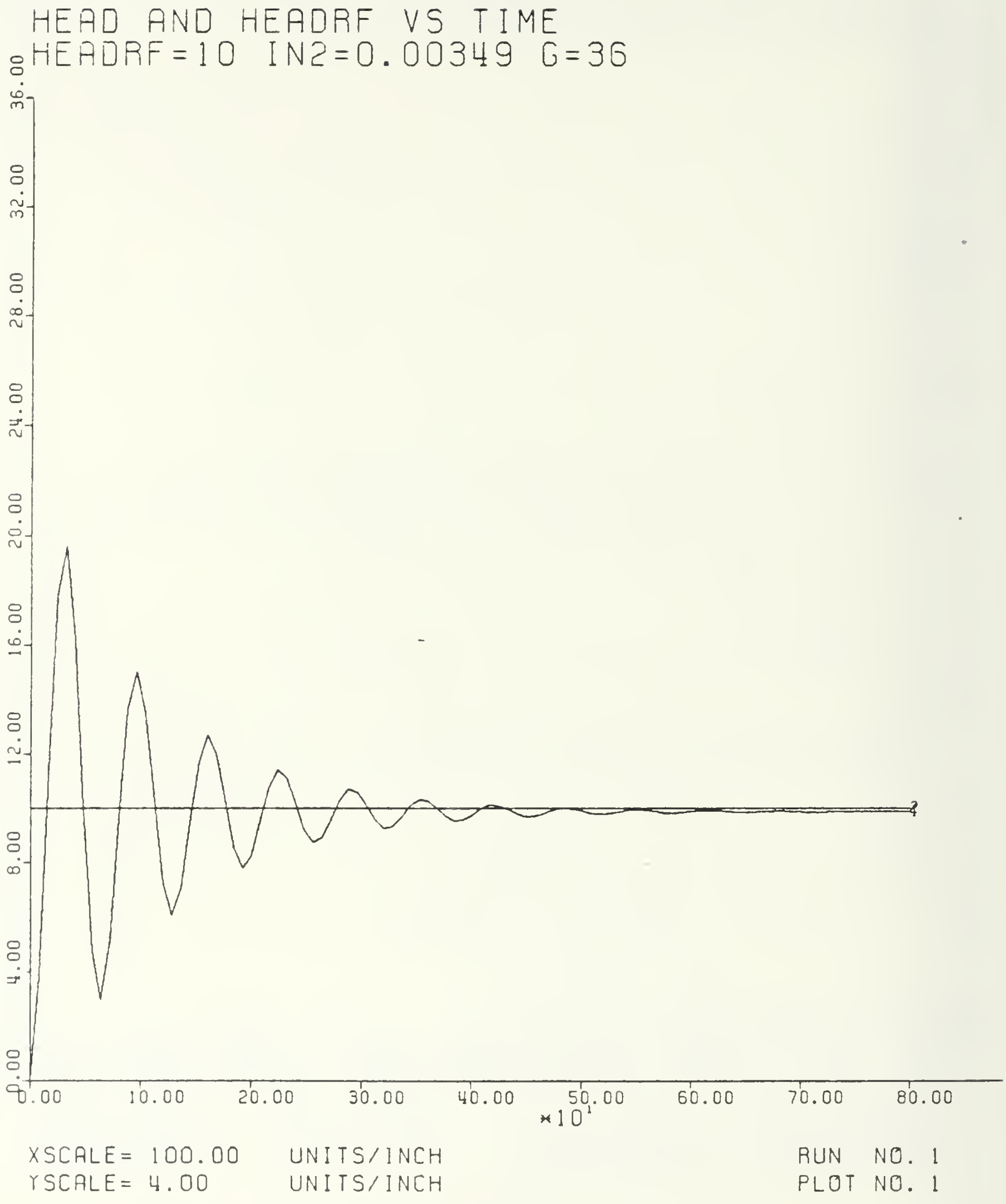

Figure 2.16 Ship Heading(1) and Heading Command(2) with Disturbance and G=36.

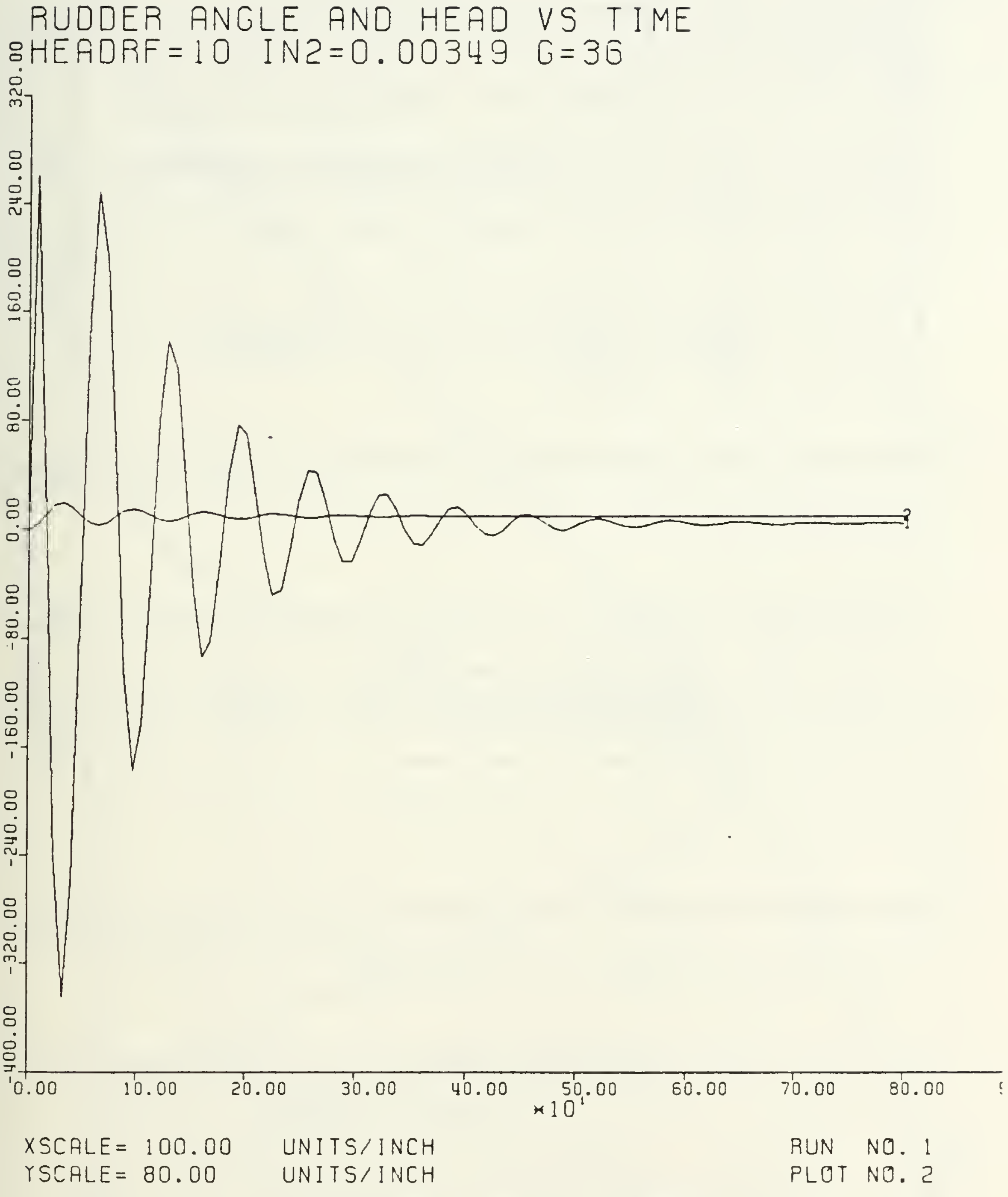

Figure 2.17 Rudder Angle(1) and Ship Heading(2) with Disturbance and G=36.

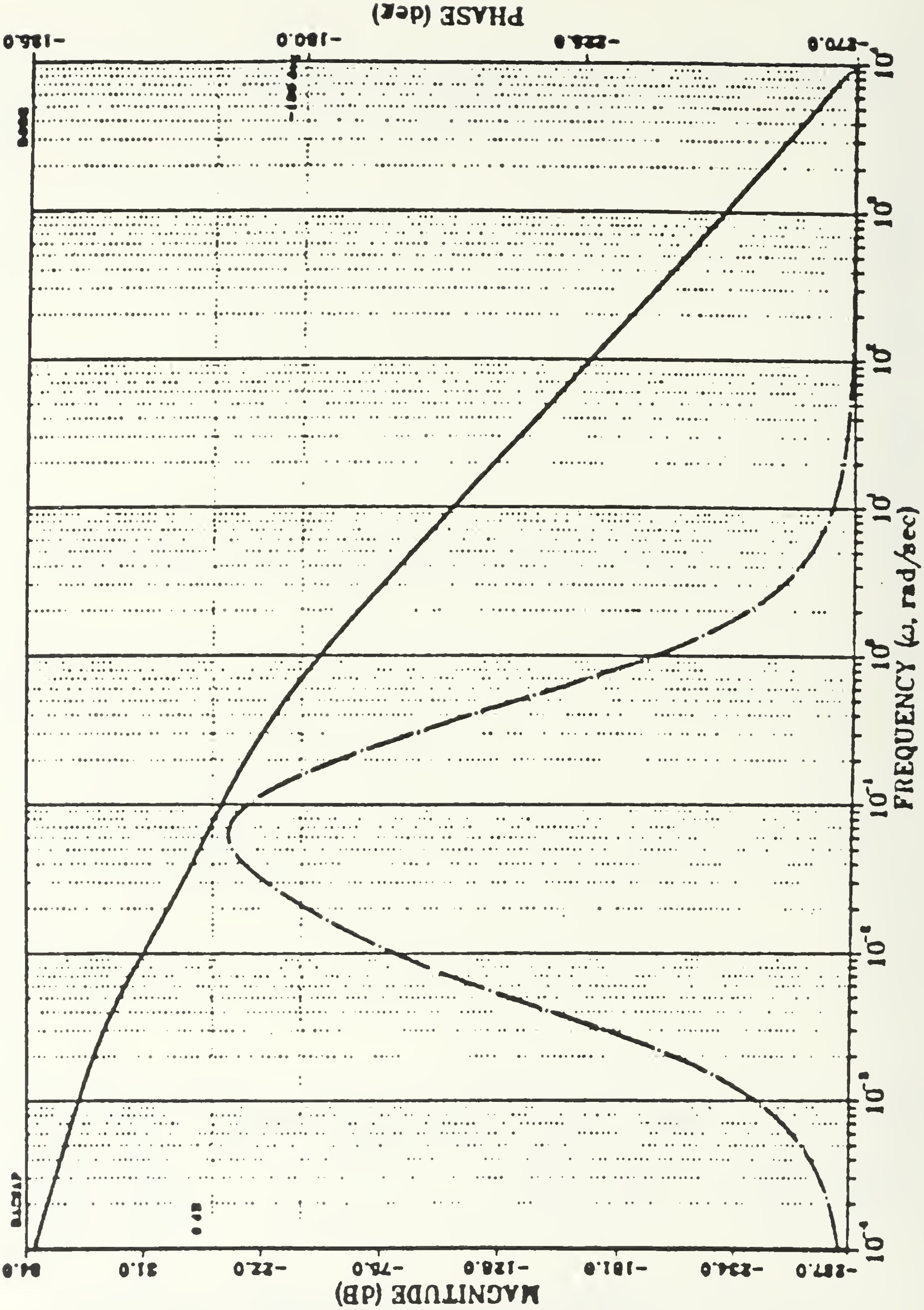

Figure 2.18   Bode Plot of the System with Steering Servo.

C. IMPROVEMENT OF THE SYSTEM

Now the system is stable but the rudder angle is too large which is not practical at all. It is necessary to improve the system performance by using a compensator to obtain acceptable transient and rudder angle performances.

1. Cascade Lead Compensation

Lead filter compensation has a transfer function as follows:

$$\frac{1}{\alpha}\frac{(s+Z)}{(s+P)} = \frac{P}{Z}\cdot\frac{Z}{P}\cdot\frac{(1+\frac{1}{Z}s)}{(1+\frac{1}{P}s)} = \frac{1+\frac{1}{Z}s}{1+\frac{1}{P}s}$$

Where $\alpha = Z/P$ and $P>Z$. The system is shown in Figure 2.19.

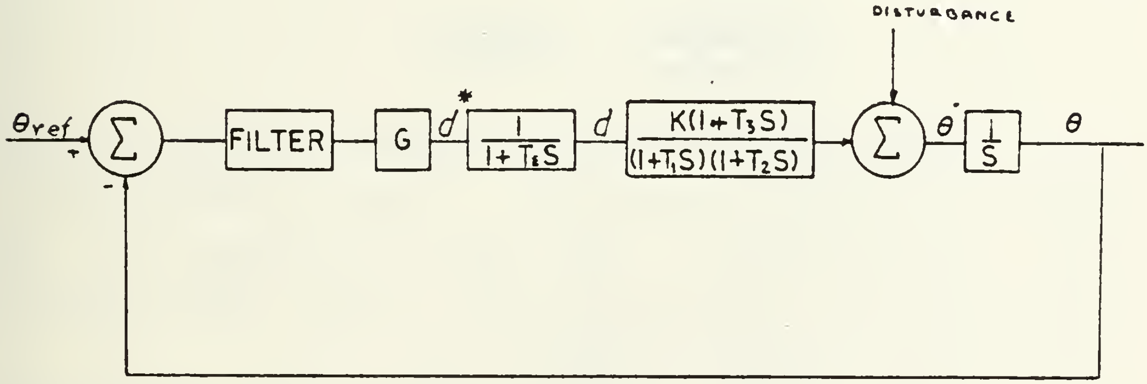

Figure 2.19 The System with the Compensator.

The characteristic equation is:

$$1+\frac{(G/\alpha)K(1+T3s)(s+z)}{s(s+p)(1+T1s)(1+T2s)(1+T_{\varepsilon}s)} = 0$$

$$1+\frac{-0.0434(G/\alpha)(s+p)(1+20s)}{s(s+p)(1-269.3s)(1+9.3s)(1+1.7s)} = 0$$

$$s(s+p)(1-269.3s)(1+9.3s)(1+1.7s)-0.0434(G/\alpha)(s+\alpha p)(1+20s) = 0$$

$$4257.633s^5+(2946.49+4257.633p)s^4+(258.3+2946.49p)s^3 + \{-1+258.3p+.868(G/\alpha)\}s^2+\{(-1+.868G)p+.0434(G/\alpha)\}s+.0434Gp = 0$$

From this equation, the NPS PAROLE program was used to find the best values of P and Z. The family of root loci are given on Figure 2.20.

From experience a good value of α was 0.1 and we select the damping ratio about 0.42. We obtain:

$$P = 0.4$$
$$\alpha = 0.1$$
$$Z = \alpha P = 0.04$$

Hence the transfer function of the lead filter compensator is:

$$\frac{1+\frac{1}{0.04}s}{1+\frac{1}{0.4}s} = \frac{1+25s}{1+2.5s}$$

Figure 2.21-2.24 are the computer outputs of Figure 2.19 with different values of G. It can be observed that to have a quick response a high gain is necessary but this could demand an excessive operation of the rudder which can be bad for the following reasons:

(1) To get a quick response, faster rudder operation and greater rudder angle are needed.

(2) This faster response may cause accelerations that are too sharp for personnel aboard ship.

(3) Too much rudder action would cause the rudder machine with all the hardware to have its life reduced.

In Figure 2.22 - 2.24 the system reaches steady state in very short time but the rudder angle is too high.

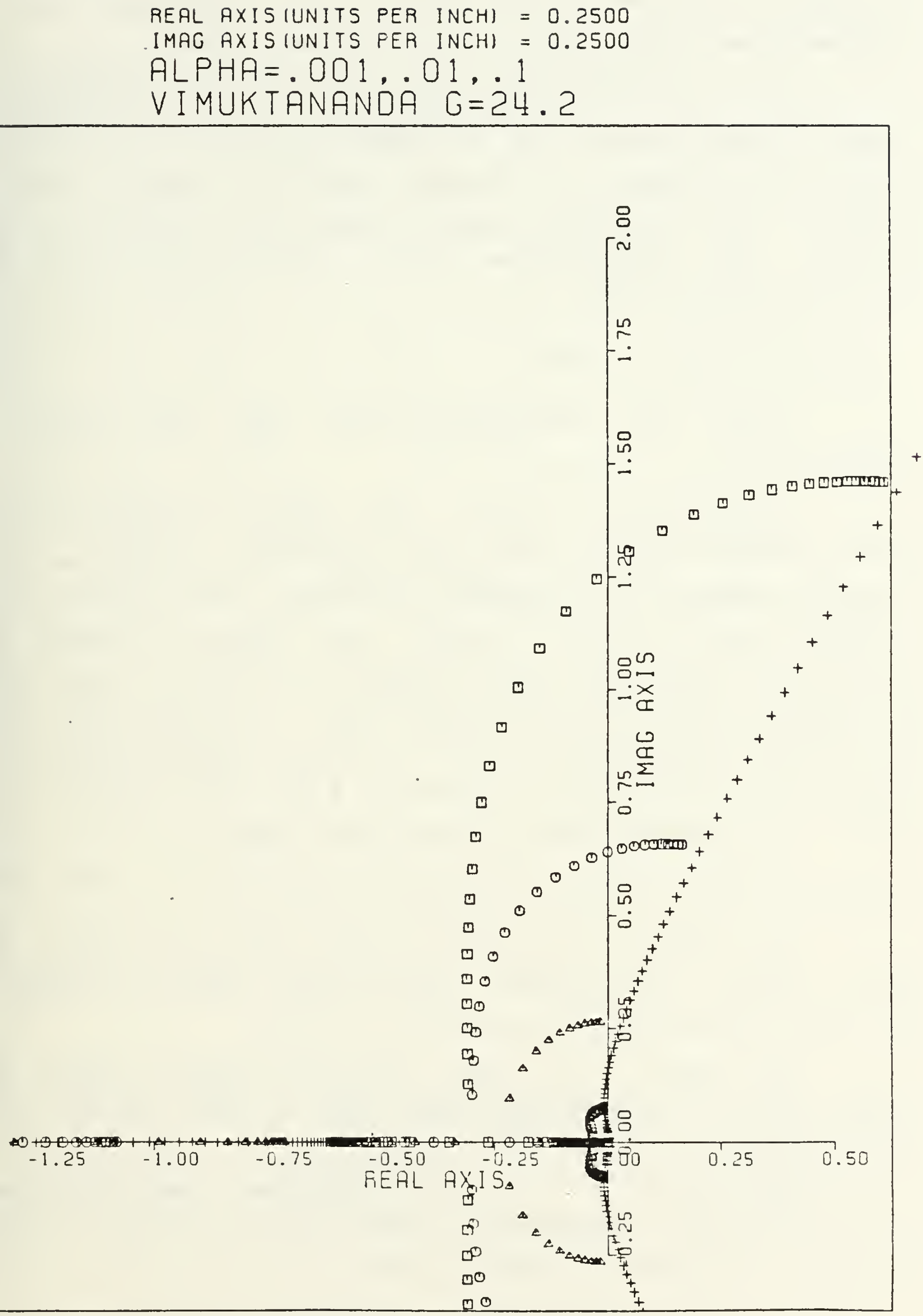

Figure 2.20 Family of the Root Loci.

In Figure 2.21 the rudder angle is at the limit but the system takes a long time to reach steady state.

So,it was necessary to reduce the rudder angle and simultaneously reduce the settling time of the system. In order to introduce a limiting value of rudder rate,the steering gear transfer function must be replaced in the system. The block diagram for an equivalent circuit was given on Figure 2.25.

Where $K3 = 1/T_{\varepsilon} = 0.588$

With this transformation,we have the system on Figure 2.26 .

Figure 2.27 - 2.30 are the computer outputs of this block diagram with the gain selected before. We can see that when the value of the gain(K1) is greater than 10,the system reaches steady state in a short time (about 3 minutes for K1=10) but the rudder angle reaches the limit on one side. In Figure 2.30,K1=3.5,the rudder angle is within the limits but the settling time is still too long. Then we must try to find a value of gain(K1) between 3.5 and 10 to get the best results for rudder angle and settling time.

Figure 2.31 - 2.33 are the outputs of this trial with gain:4.6,5.3 and 6. We can see that:

For gain = 6 the settling time is about 450 sec.(7.5min.) the maximum rudder rudder angle is about 28 deg. and the heading error about 0.77 deg..

For gain = 5.3 the settling time is about 470 sec.(7.8min.) the maximum rudder angle is about 26 deg. and the heading error about 0.9 deg..

For gain = 4.6 the settling time is about 510sec.(8.5min) the maximum rudder angle is about 22 deg. and the heading error about 1.1 deg..

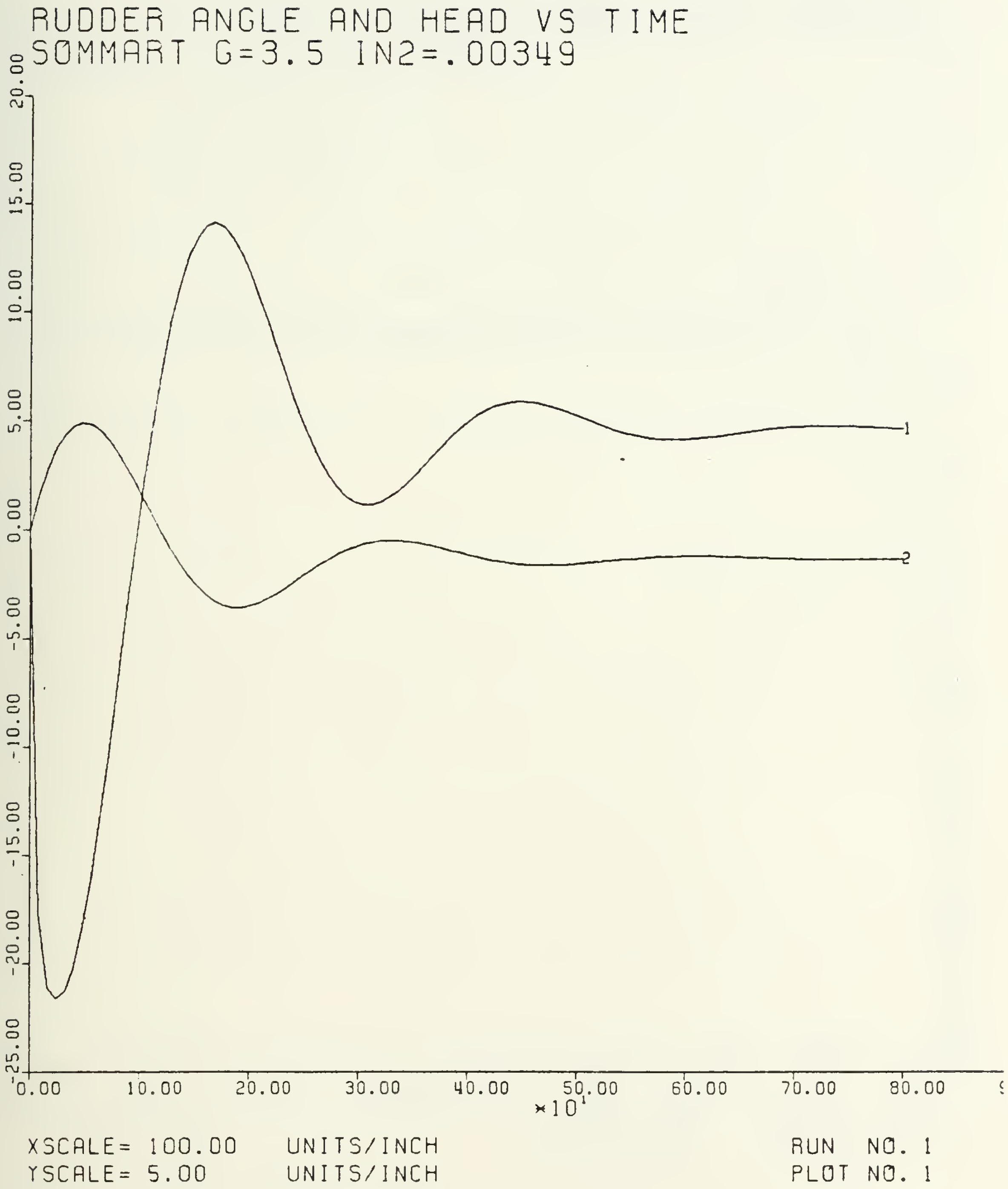

Figure 2.21 Rudder Angle(1) and Ship Heading(2) without Limiter and G=3.5.

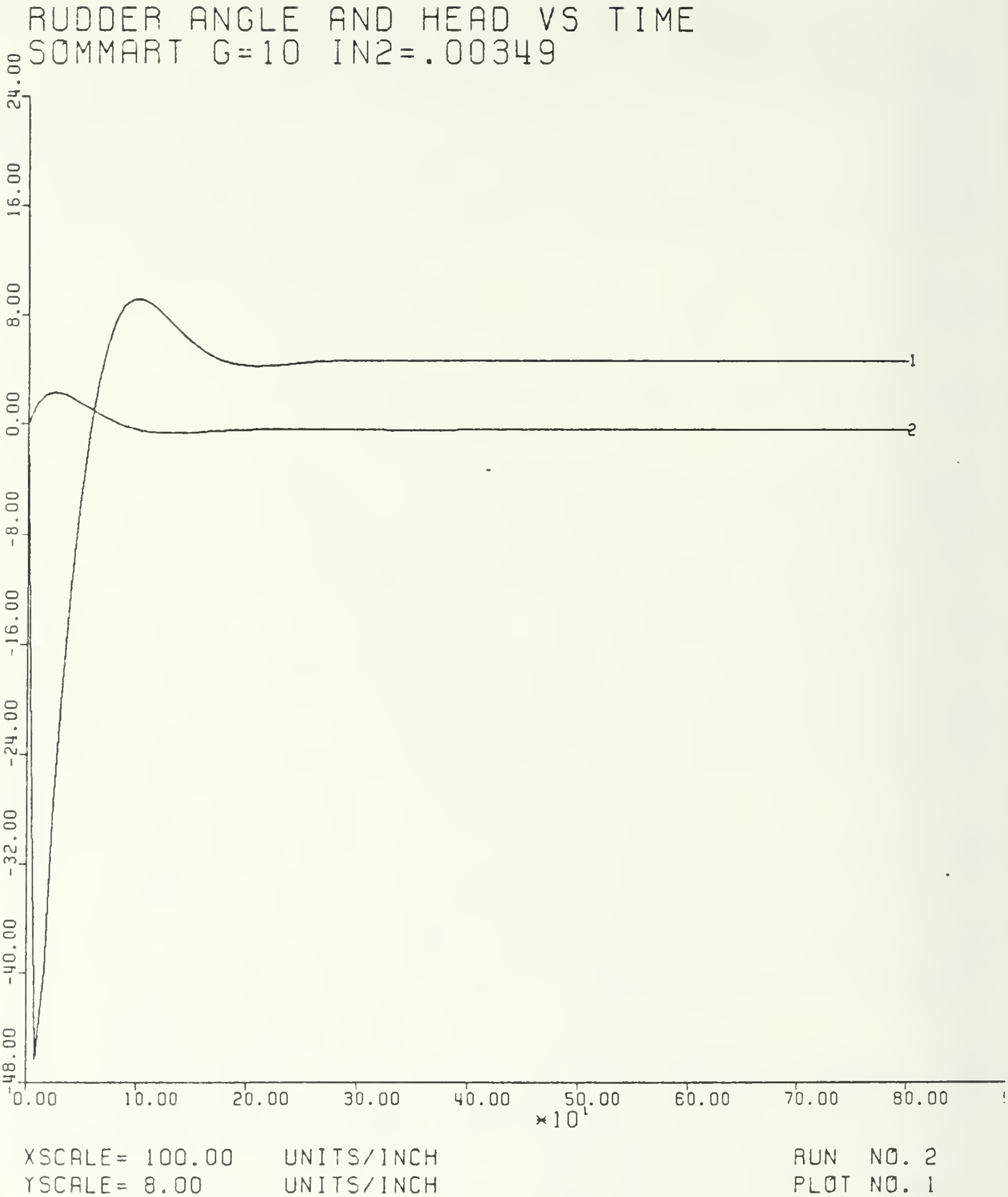

Figure 2.22 Rudder Angle(1) and Ship Heading(2) without Limiter and G=10.

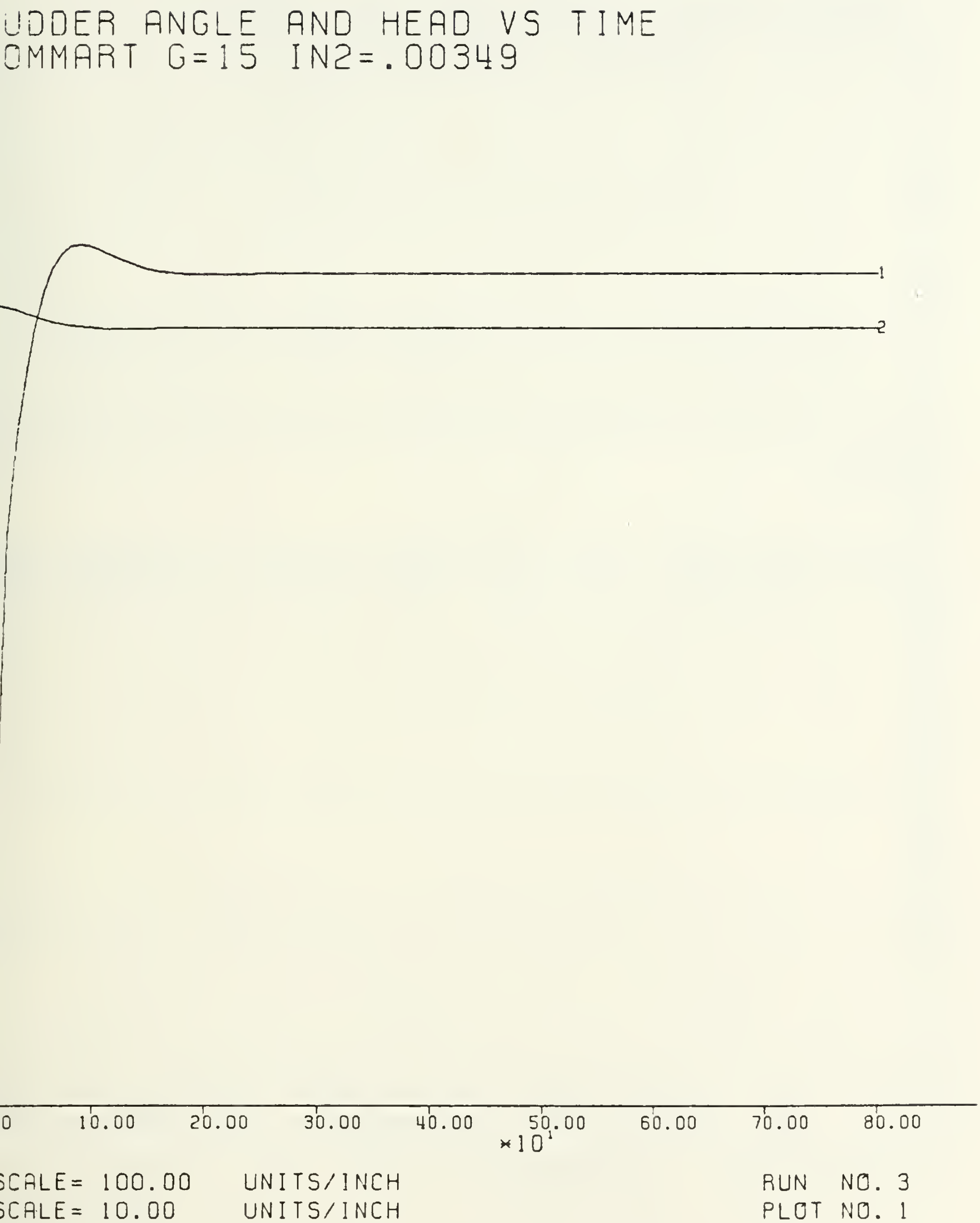

Figure 2.23 Rudder Angle(1) and Ship Heading(2) without Limiter and G=15.

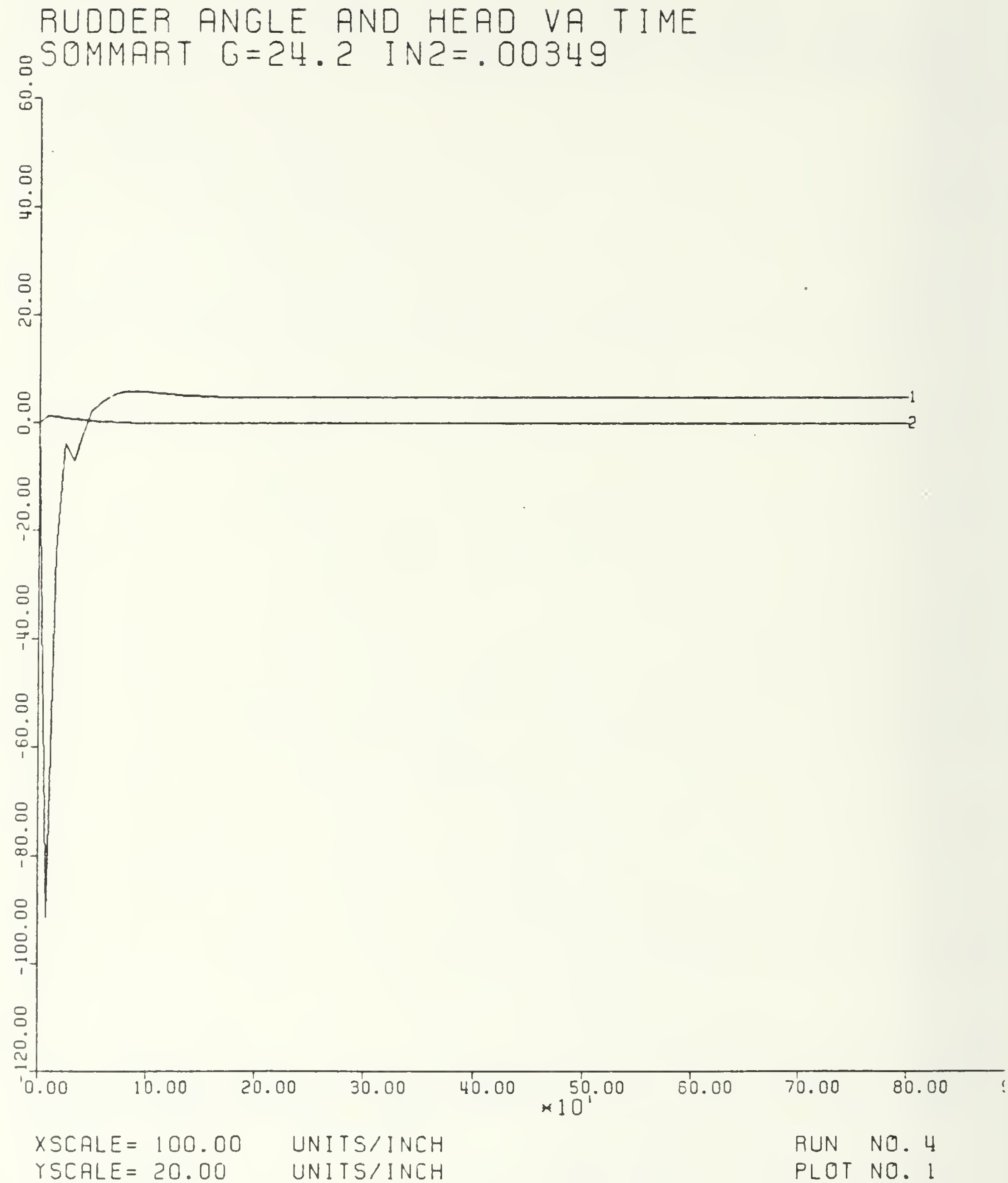

Figure 2.24 Rudder Angle(1) and Ship Heading(2) without Limiter and G=24.2.

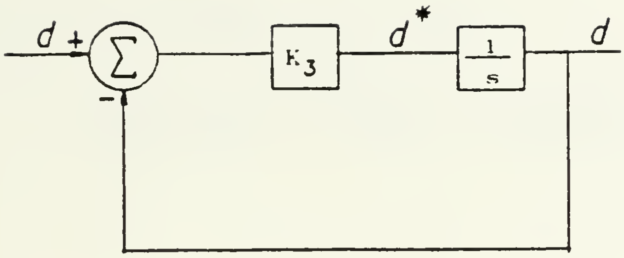

Figure 2.25   Block Diagram of the Steering Gear.

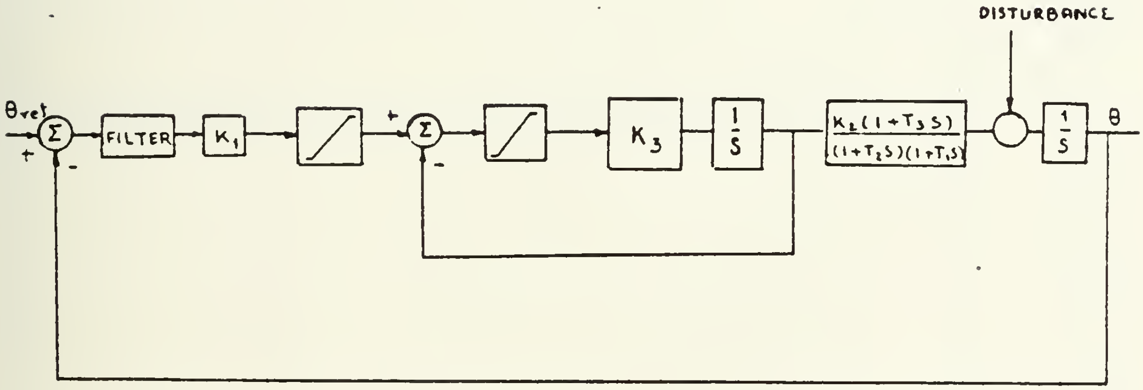

Figure 2.26   The Complete Block Diagram for Course-Keeping.

So we can conclude that the best value for Course-keeping with the limiter is 4.6. Figure 2.34 is the Bode plot of this system with phase margin = 42.2 degrees and gain margin = -15.97 DB that are better than the Bode plot of Figure 2.18. Then the system of Course-keeping is satisfactory.

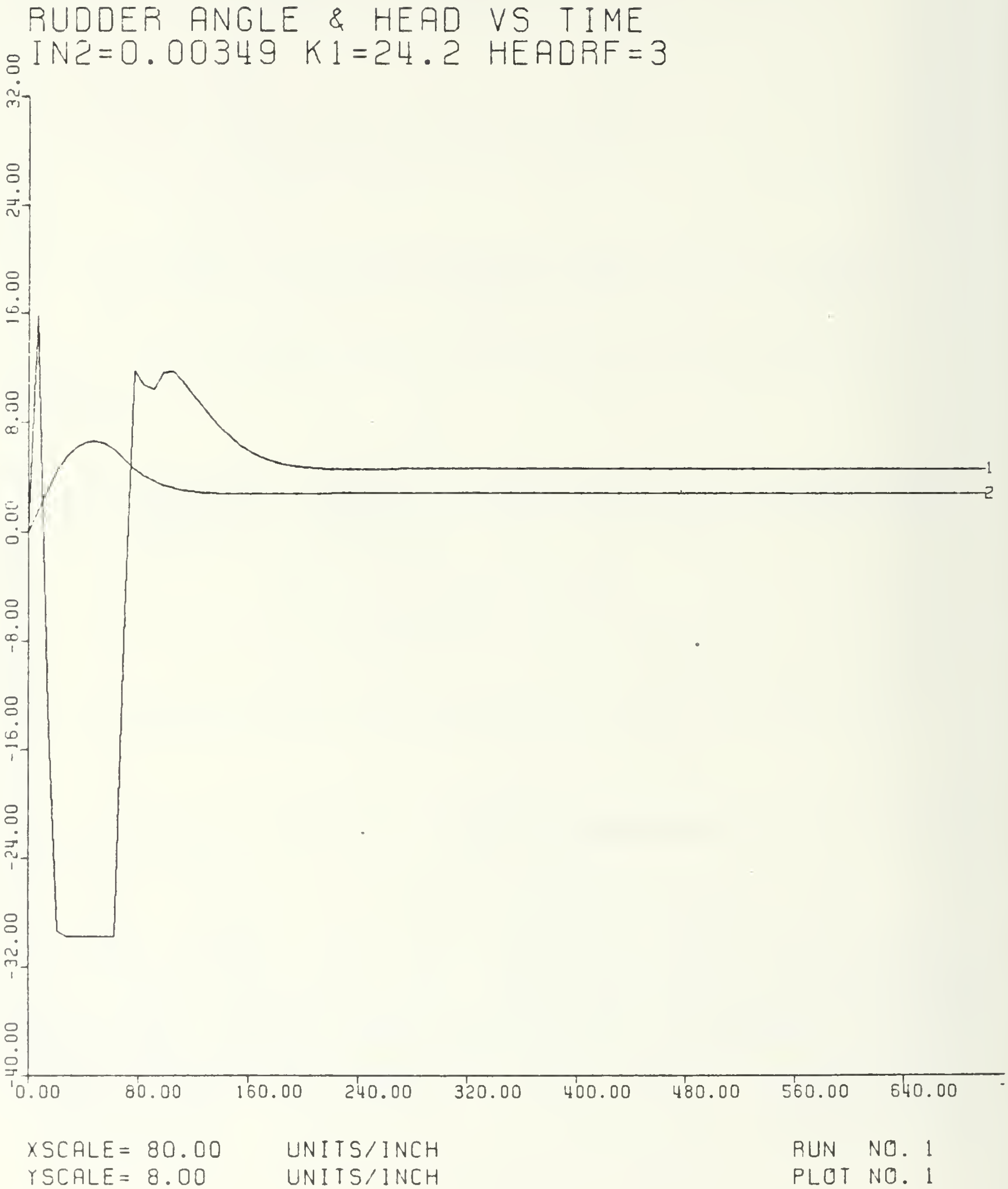

Figure 2.27 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=24.2.

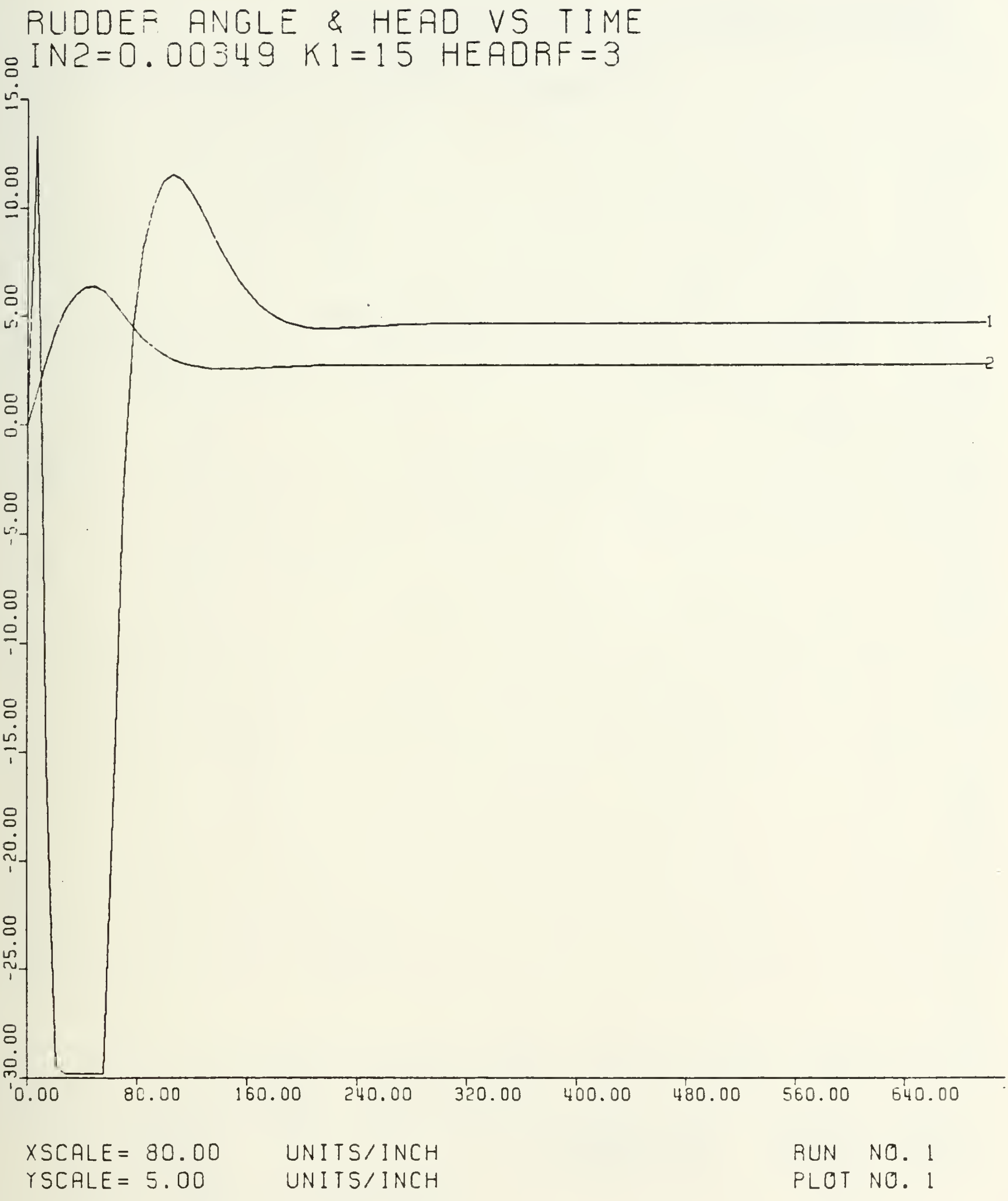

Figure 2.28 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=15.

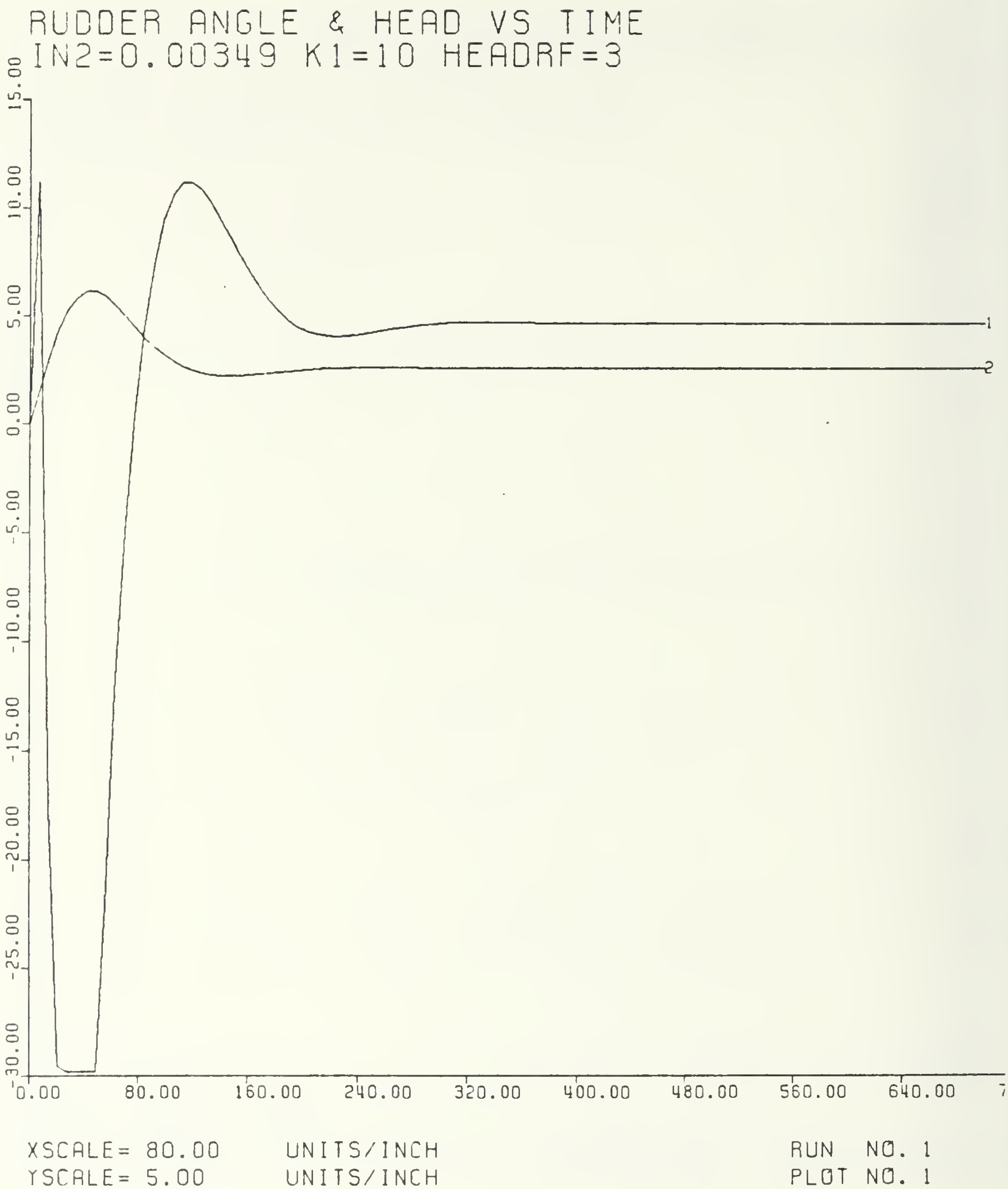

Figure 2.29 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=10.

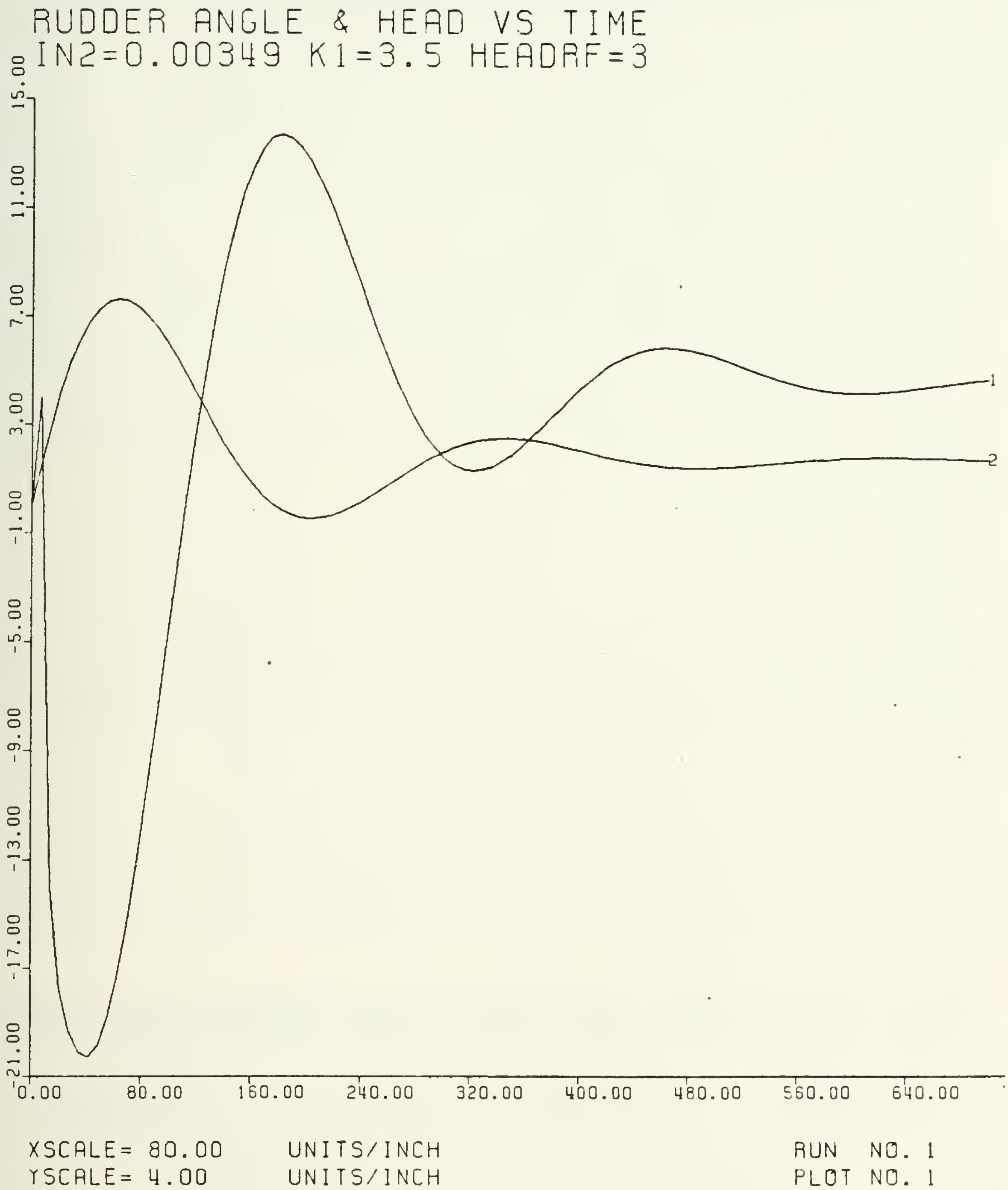

Figure 2.30 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=3.5.

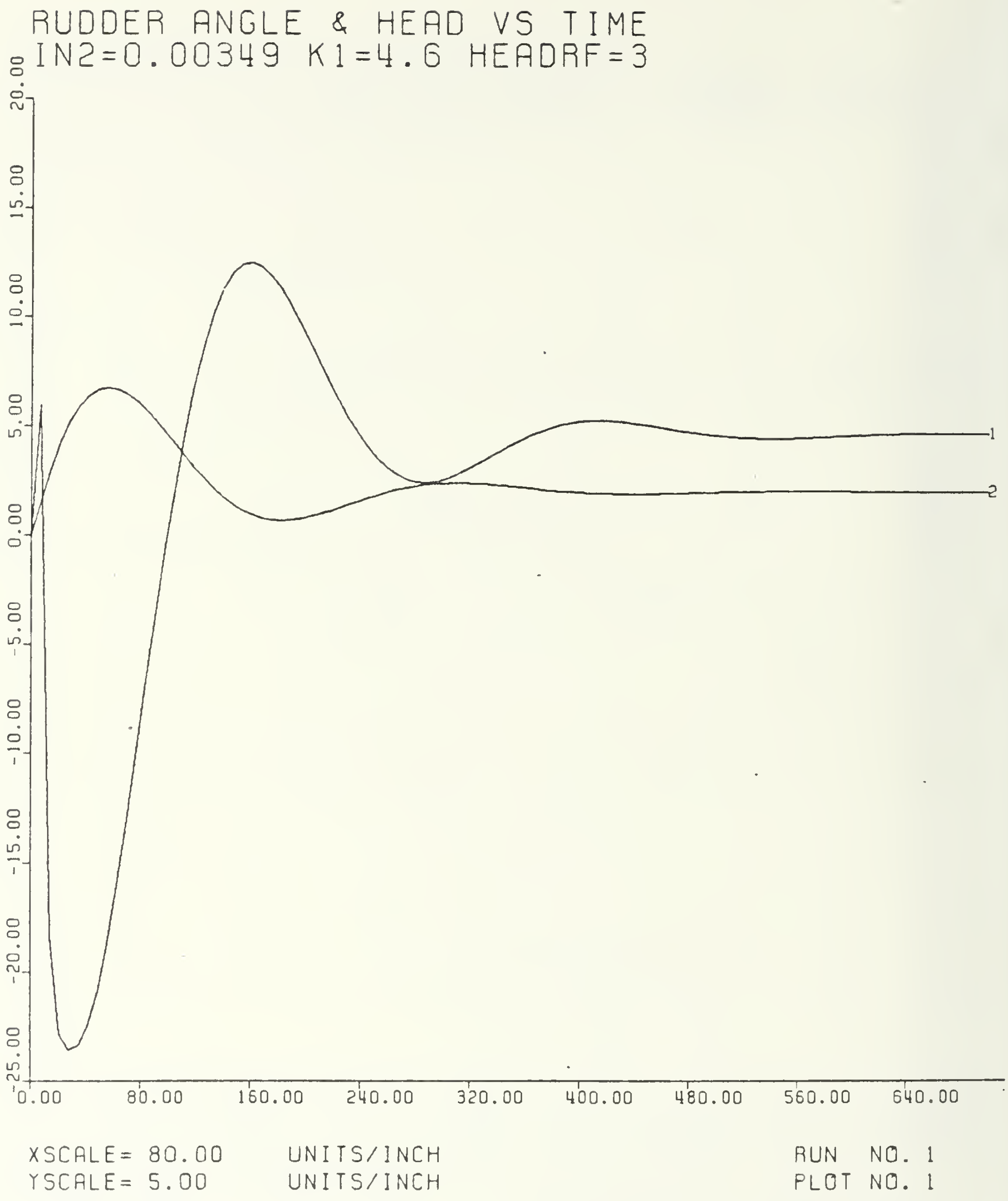

Figure 2.31 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=4.6.

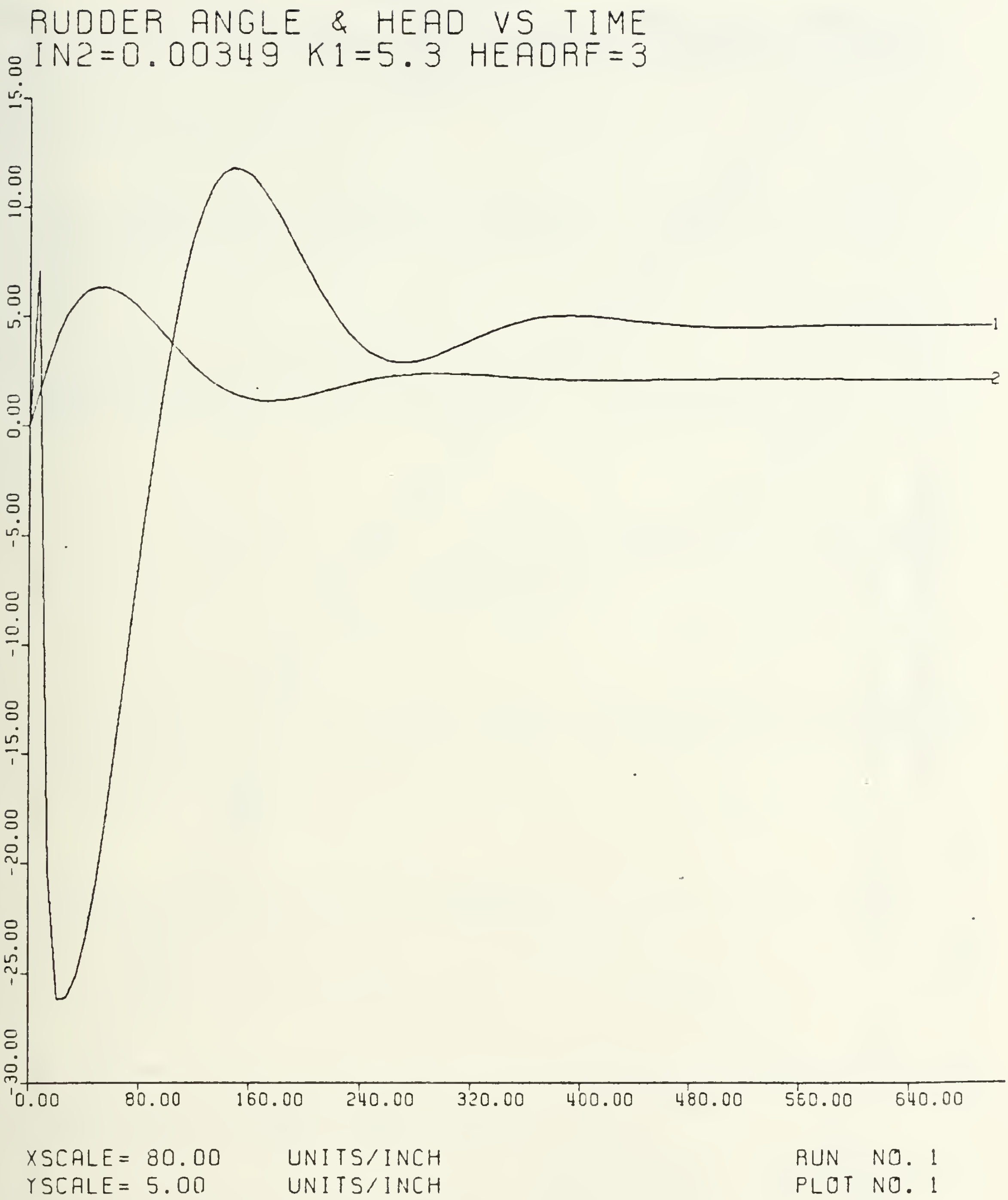

Figure 2.32 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=5.3.

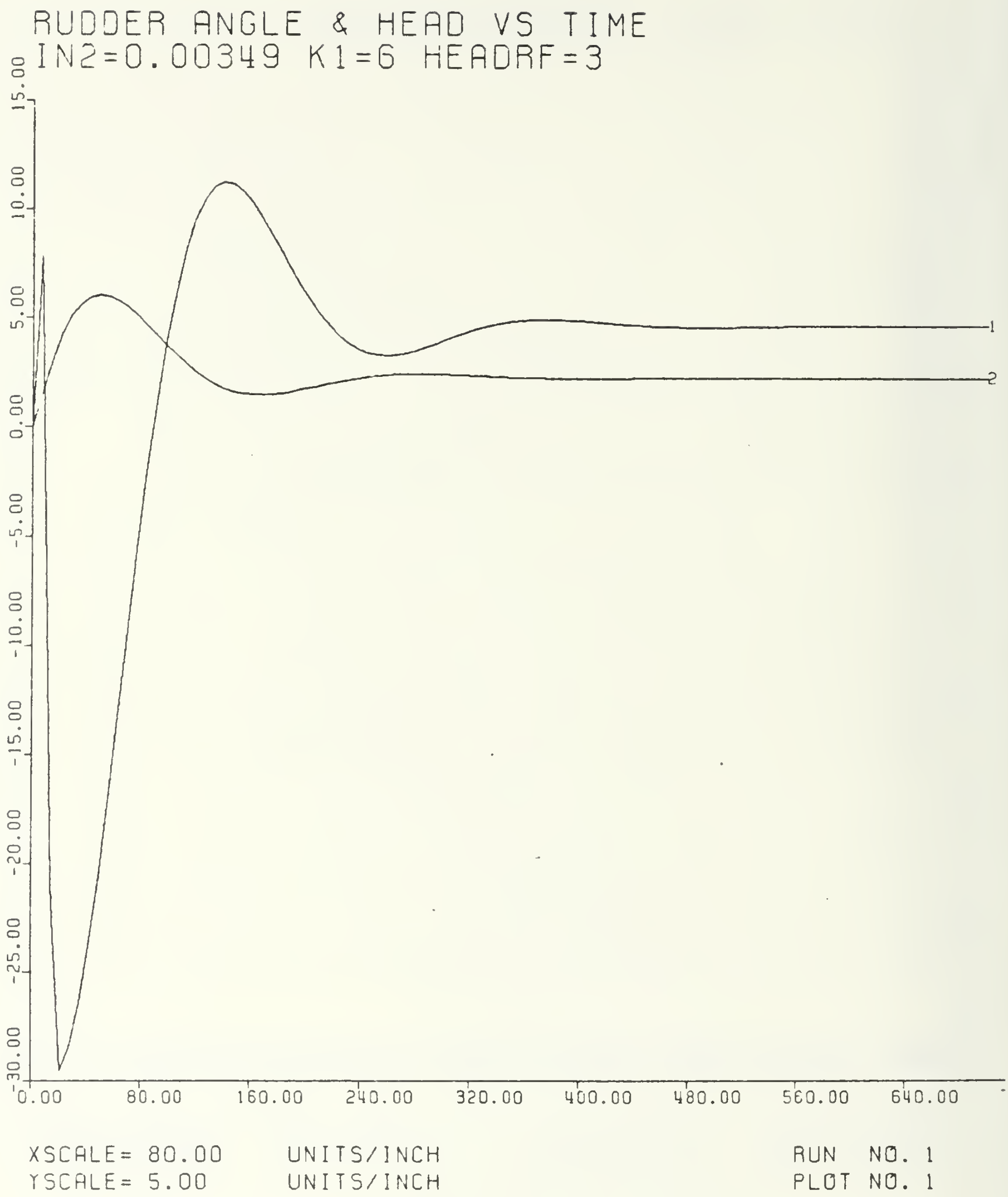

Figure 2.33 Rudder Angle(1) and Ship Heading(2) with Limiter and K1=6.

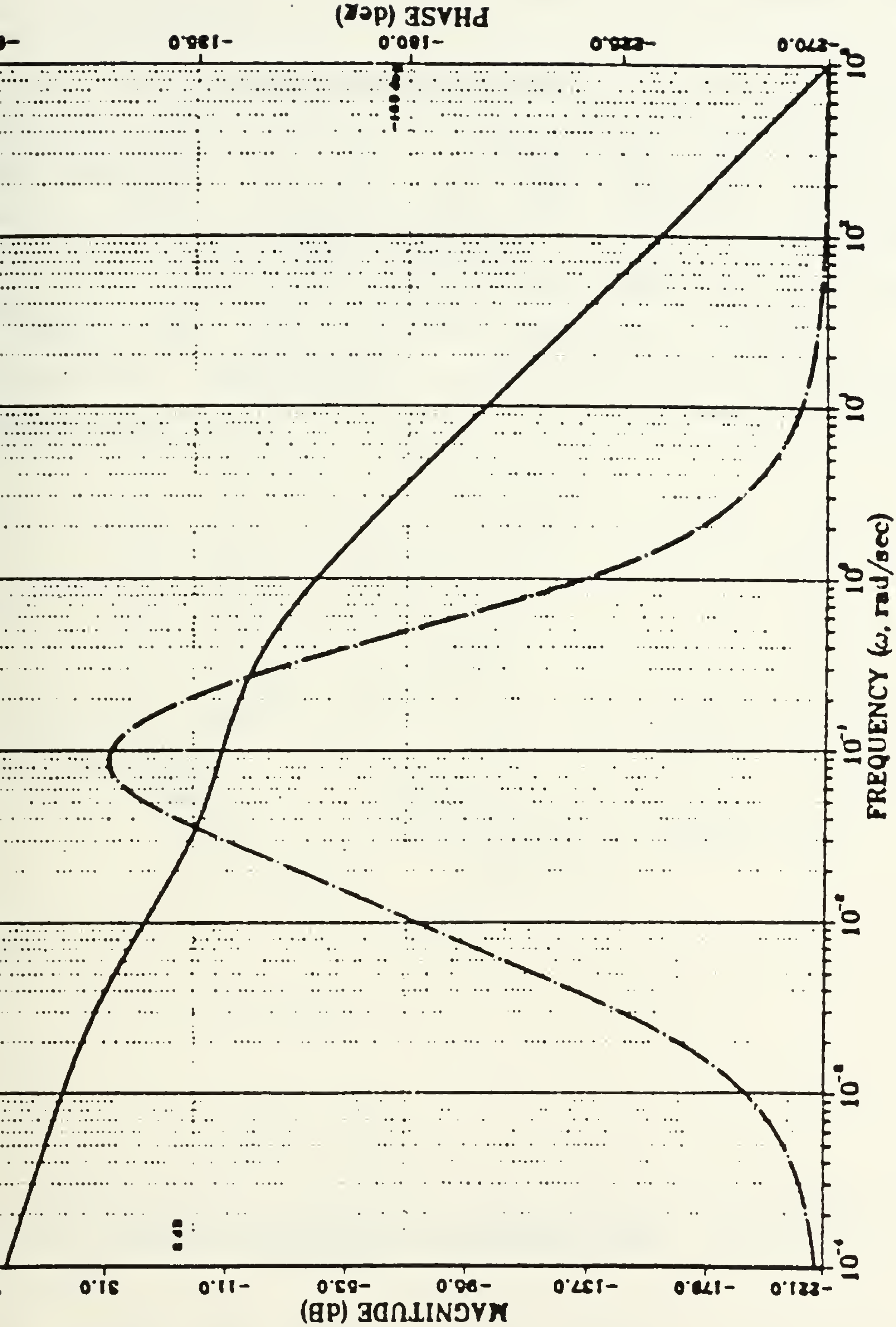

Figure 2.34 Bode Plot of the System with Steering Servo and Filter.

III. TRACK FOLLOWING

Using the ship heading controller obtained previously, and assuming that the velocity of the ship is constant (at 14 knots) during underway on the open sea, the position of the ship can be found at any time.

In order to find the position of the ship, a right hand rectangular coordinate system is established, the origin of which is chosen to be in the body itself, as shown in Figure 3.1.

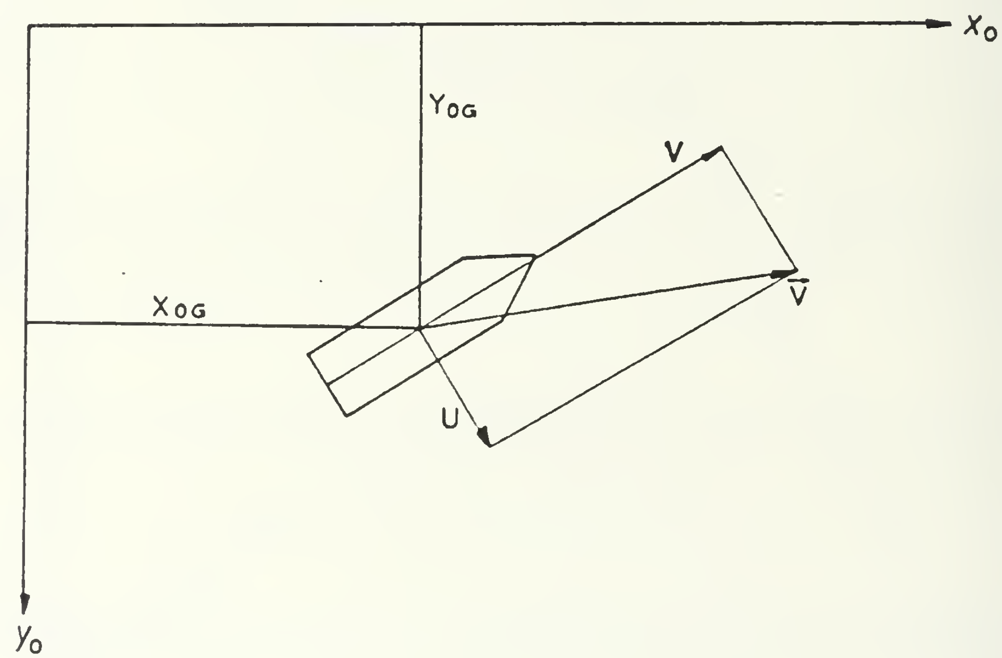

Figure 3.1 Orientation of the Space Axis(X0,Y0) and the Moving Axis(X,Y).

The origin and the axes are fixed with respect to the body but movable with respect to other systems of coordinate

axes fixed in space.It is assumed that the two systems coincide at t=0.

The transformation from the ship to space coordinate system is defined by the following relations,obtained from Figure 3.1

$$\dot{X} = V\cos\Theta + U\sin\Theta$$
$$\dot{Y} = V\sin\Theta - U\cos\Theta$$

and

$$X = X0+\int\dot{X}dt$$
$$Y = Y0+\int\dot{Y}dt$$

where

$\dot{X}$ = Velocity in X-direction
$\dot{Y}$ = Velocity in Y-direction
X0 = Initial position of X
Y0 = Initial position of Y
V = Ship velocity
U = Lateral velocity

Assuming constant velocity and no lateral force,the equations become:

$$\dot{X} = V\cos\Theta$$
$$\dot{Y} = V\sin\Theta$$

and

$$\dot{X} = dx/dt$$
$$\dot{Y} = dy/dt$$

then

$$X = X0 + \int dx$$
$$Y = Y0 + \int dy$$

Knowing initial values of X and Y,the coordinates of the ship are calculated. Figure 3.2 is the block diagram of this procedure.

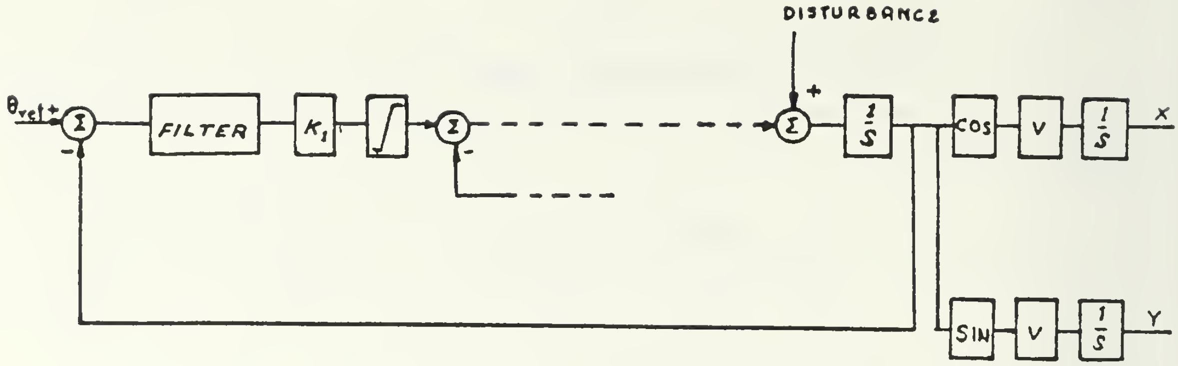

Figure 3.2 Course-Keeping and Coordinate Calculation.

These equations were included in the program of the Course-keeping autopilot in order to find the position of the ship.

Figure 3.3-3.4 are the output of this program.

The purpose of the Track following is to keep the ship following the desired trajectory from the beginning to the destination. When the ship is not on the track a course correction must be calculated to return the ship to the track. The corrected course is a function of the distance to the track.

A. FINDING THE COURSE CORRECTION

Initially the navigator must design the trajectory from the beginning point to the destination on the map. He has to know the course and speed. When the ship is underway,it is necessary to know(measure) the position of the ship. Although the course of the ship may be the same as the desired course,it may not be on the desired trajectory due to the effect of sea current and wind. Therefore the navigator has to calculate a new course to keep the ship

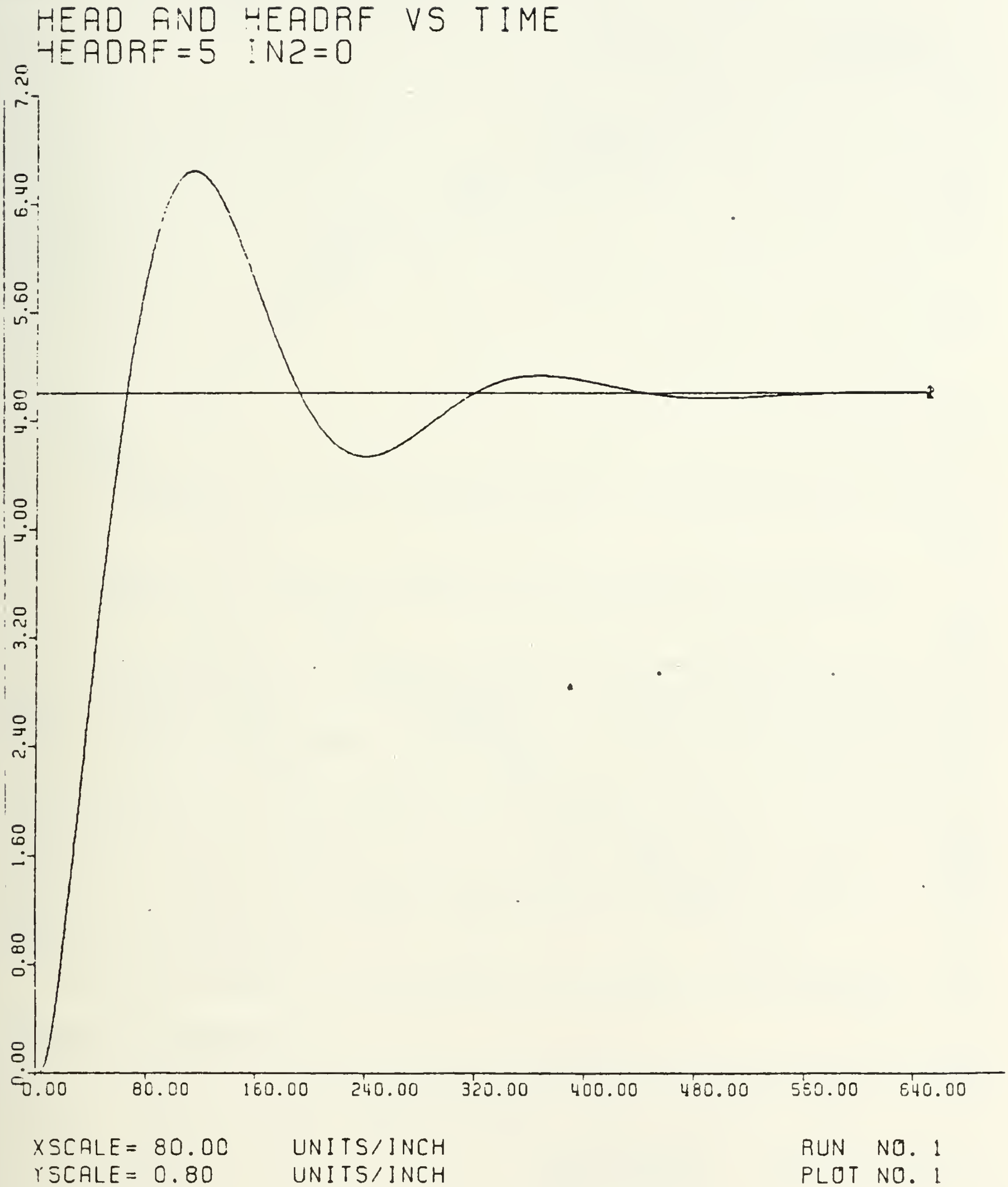

Figure 3.3 Ship Heading(1) and Desired Heading(2).

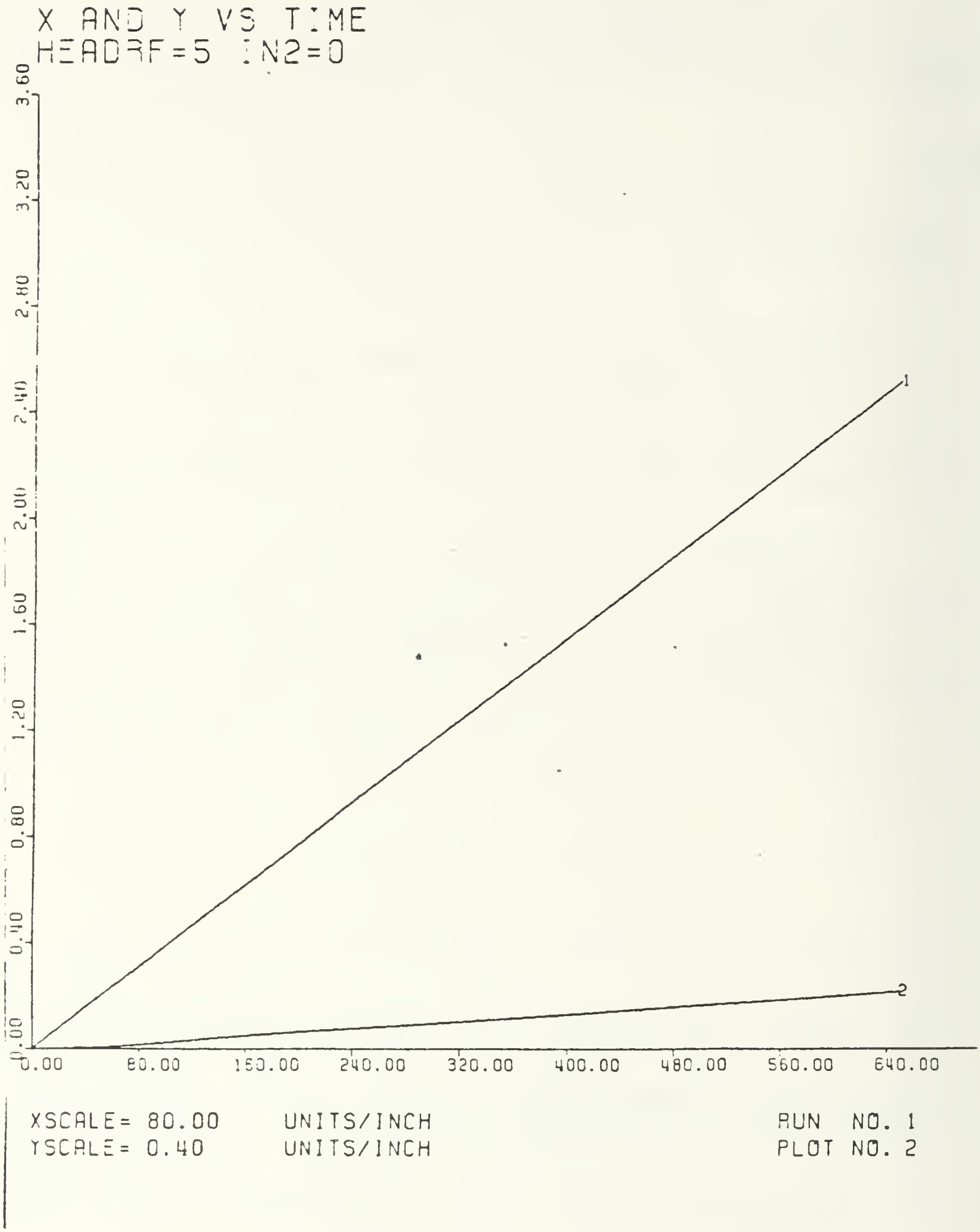

Figure 3.4 Distance in X(1) and Y(2).

following the desired trajectory until the ship reaches the destination. This situation is depicted in Figure 3.5.

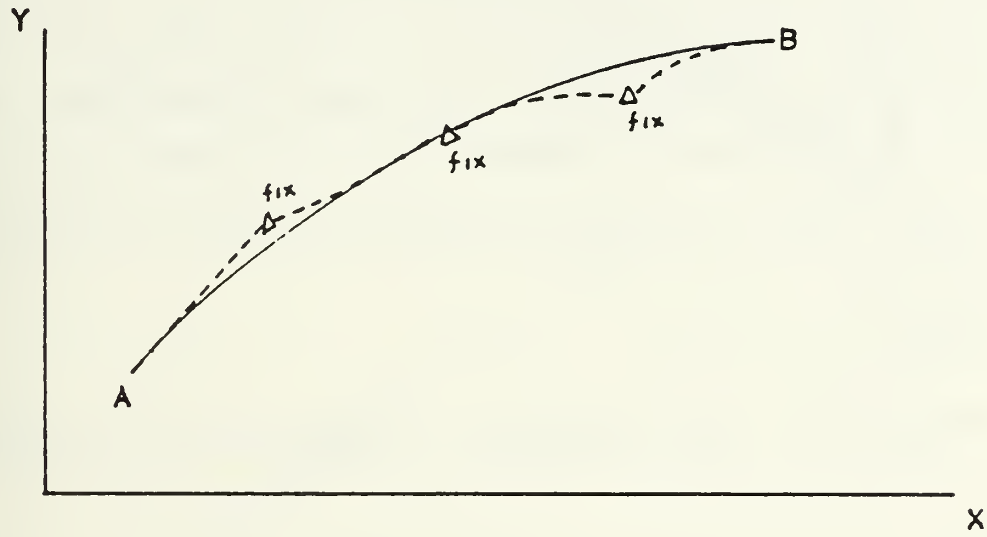

Figure 3.5 The Trajectory Followed by the Ship.

The procedure of an autopilot for track-following is the same as that used by a navigator. First the coordinates of the desired trajectory are stored in the computer as shown in Figure 3.6 The position of the ship is measured by NAVSTAR/GPS.The computer calculates the errors in X and Y positions and calculates the course correction. These errors should be zero in order to keep the ship always on the desired trajectory.

The procedure to calculate the course correction(θ_c) is shown in Figure 3.7

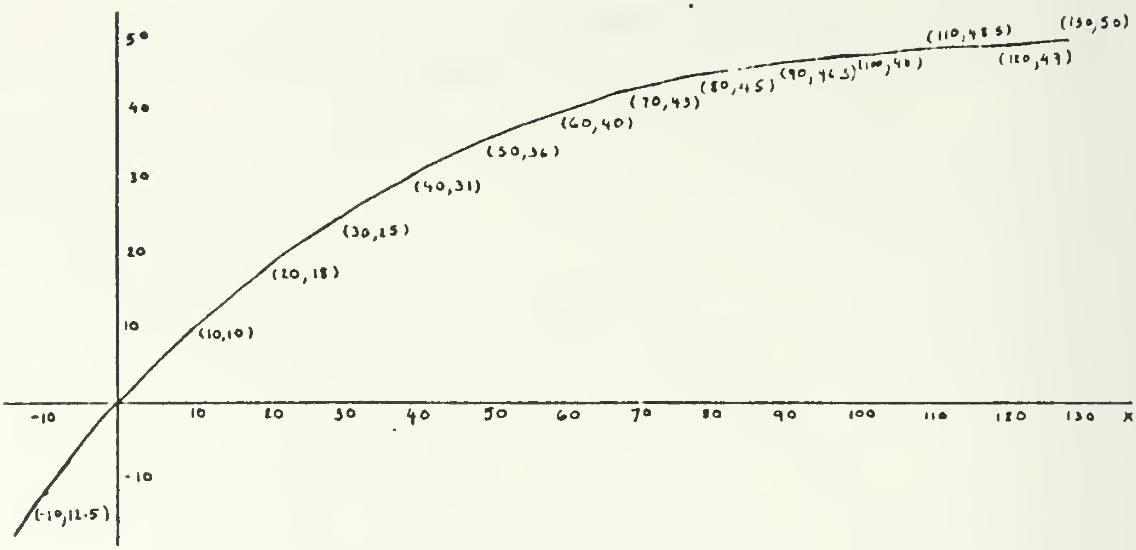

Figure 3.6 The Coordinate of The Desired Trajectory.

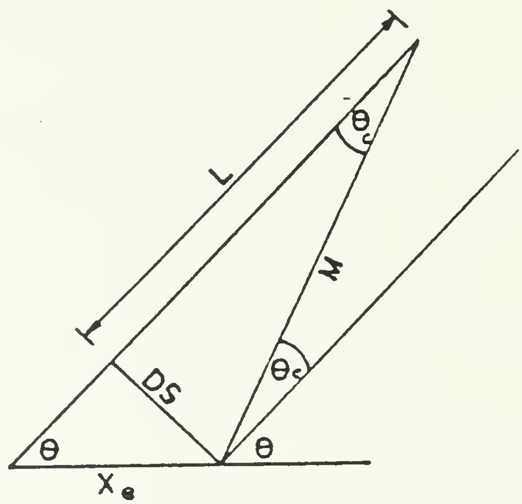

Figure 3.7 The Algorithm to Compute The Course Correction.

$$
\begin{aligned}
DS/Xe &= \mathrm{SIN}\ \theta \\
DS &= Xe\ \mathrm{SIN}\ \theta \\
M &= \sqrt{DS^2 + L^2} \\
\mathrm{SIN}\ \theta c &= DS/M \\
\theta c &= \mathrm{SIN}^{-1}\ (DS/M)
\end{aligned}
$$

B. FINDING THE DESIRED COURSE

The desired trajectory is stored in the computer,the desired course can be found in a simple way,Figure 3.8 shows the method. The X axis is divided into constant small intervals. For each point of X,the corresponding Y coordinate is found. The desired course is obtained by taking the arctangent of the result of the division between increment in Y and increment in X.

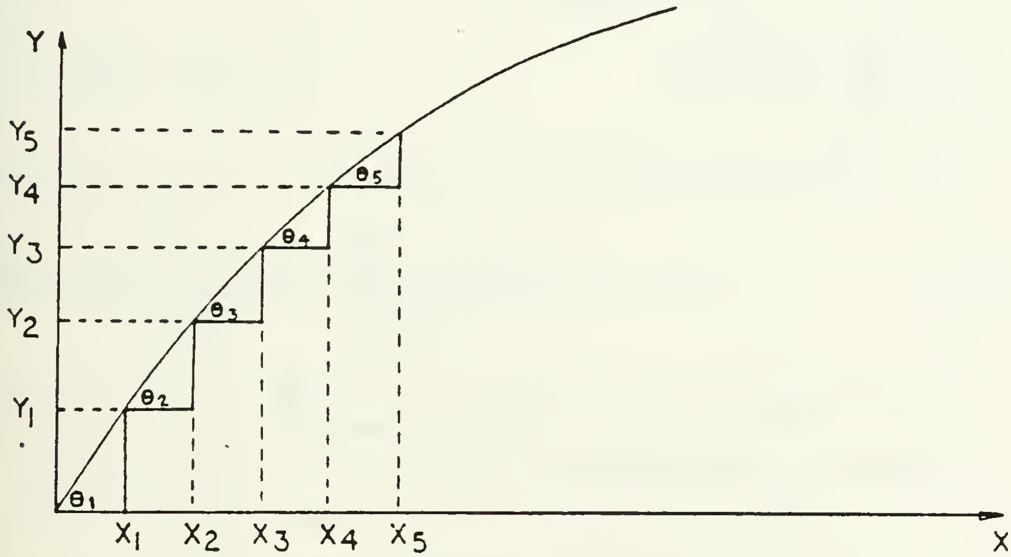

Figure 3.8 Algorithm to Compute The Desired Course.

$$\theta_1 = \tan^{-1}\left(\frac{Y_1}{X_1}\right)$$

$$\theta_2 = \tan^{-1}\left(\frac{Y_2 - Y_1}{X_2 - X_1}\right)$$

$$\theta_3 = \tan^{-1}\left(\frac{Y_3 - Y_2}{X_3 - X_2}\right)$$

$$\theta_4 = \tan^{-1}\left(\frac{Y_4 - Y_3}{X_4 - X_3}\right)$$

$$\theta_5 = \tan^{-1}\left(\frac{Y_5 - Y_4}{X_5 - X_4}\right)$$

$$\vdots$$

For selecting the value of the constant small interval of X,we consider Figure 3.9

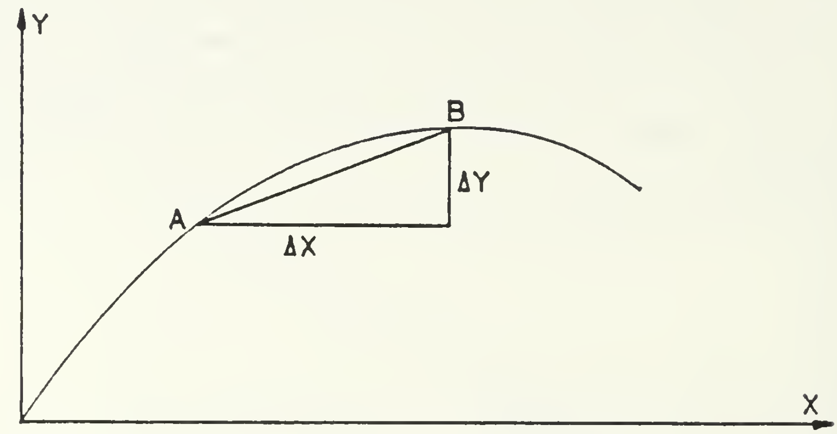

Figure 3.9 The Condition such that the Algorithm Fails.

If the value of X is big,the straight line AB is not on the curve,so the desired course is not true. To get the true desired heading the straight line AB has to be on the curve all the time. To accomplish this we have to select the value of X small enough,so the straight line AB is part of the curve.

C. FIRST ATTEMPT TO DO THE TRACK FOLLOWING

From the Figure 3.2, X and Y positions are obtained. With these values, the desired heading and trajectory are obtained. By using an integrator with the gain K4(as shown in the block diagram of figure 3.2) we will obtain a new block diagram which is shown in Figure 3.10. The purpose of the integrator is to eliminate steady state position errors.

A suitable value of integrator gain is K4=.01.The value was found by repeated simulation runs. Figure 3.11-3.14 are

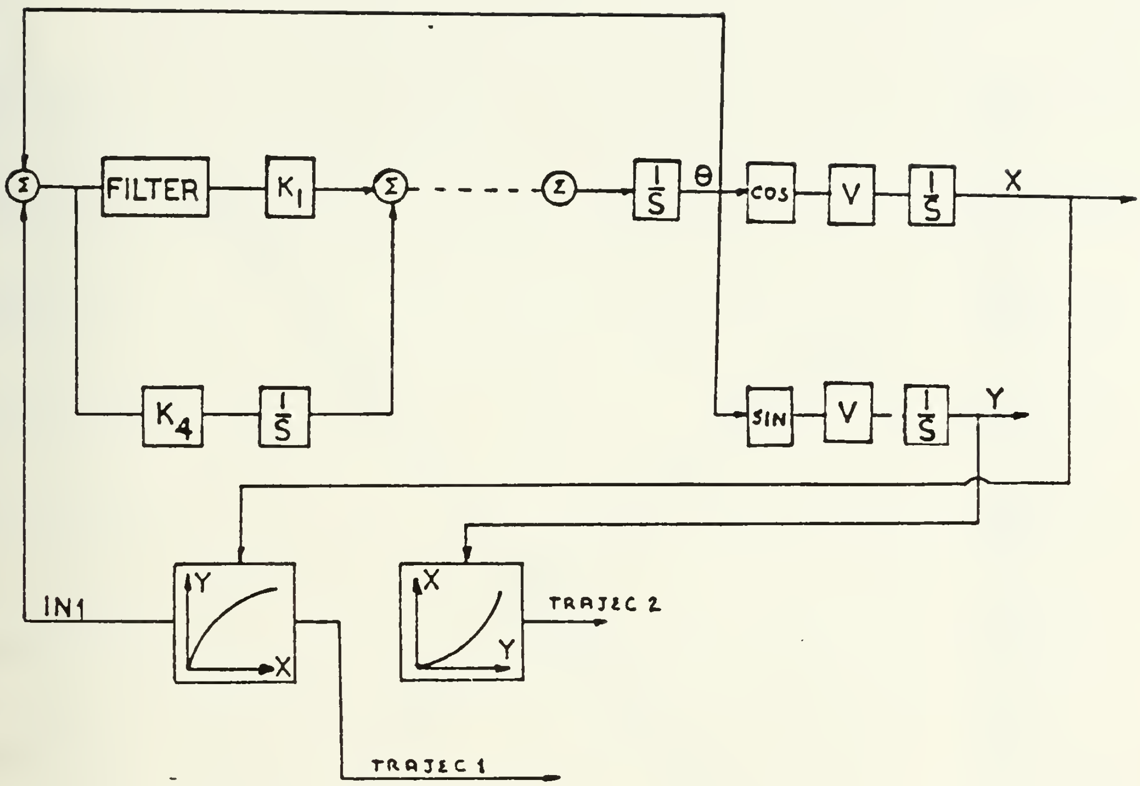

Figure 3.10 Block Diagram of An Autopilot With The Integrator.

the results obtained without disturbances. From Figure 3.11-3.12 the actual trajectory and the desired trajectory are coincident. In Figure 3.14 the time for the output to reach steady state is about 800 seconds(13.3 minutes).

The system was also simulated with disturbances. Figure 3.15-3.18 are the results with K4=.01. In Figure 3.15-3.16 the actual trajectory and the desired trajectory are not coincident but the distance between them gradually increases with time. In Figure 3.18 the time for the output to reach steady state is about 1600 seconds(26.67 minutes).

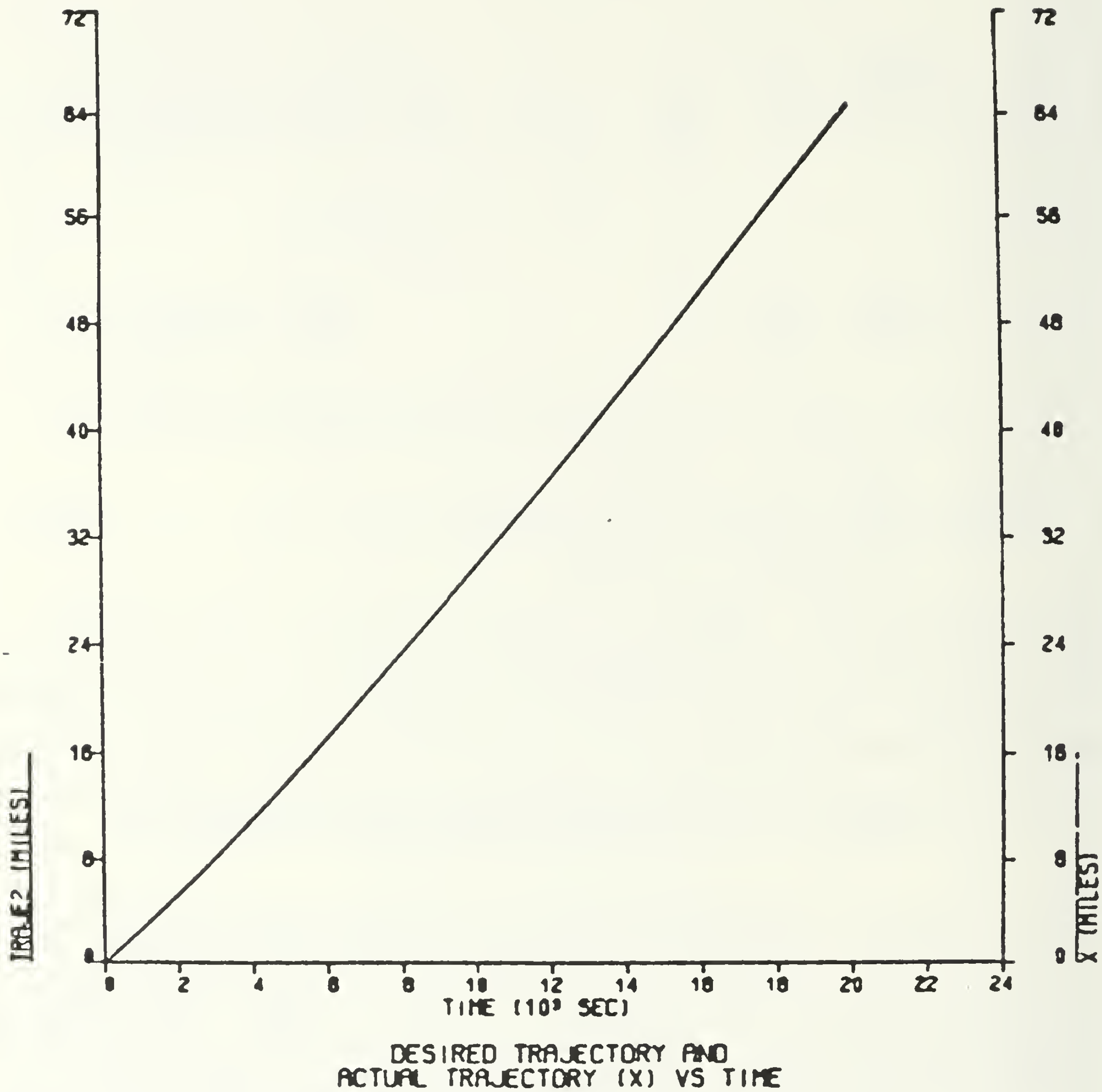

Figure 3.11 Desired Trajectory and X when K4=.01.

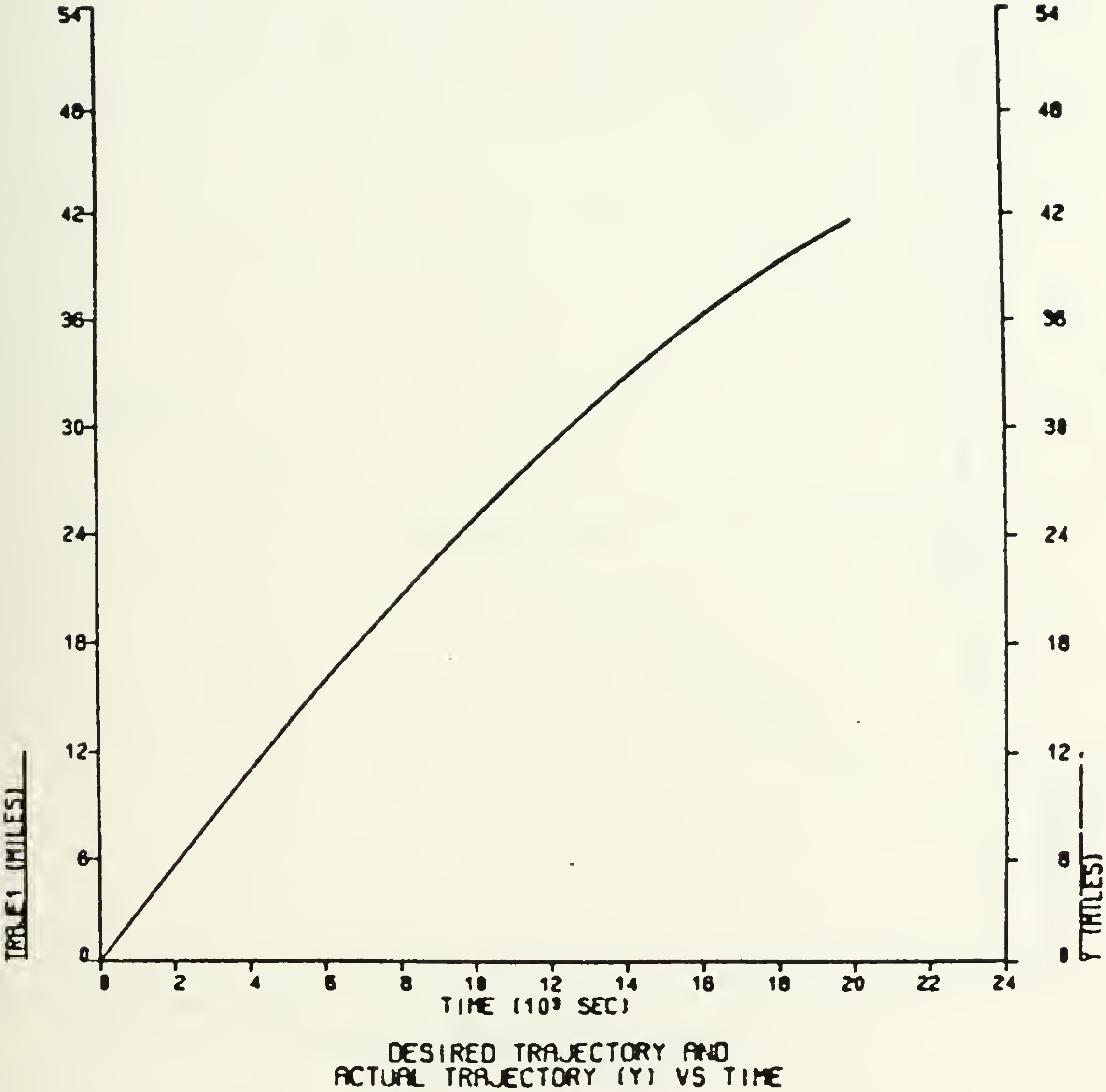

Figure 3.12 Desired Trajectory and Y when K4=.01.

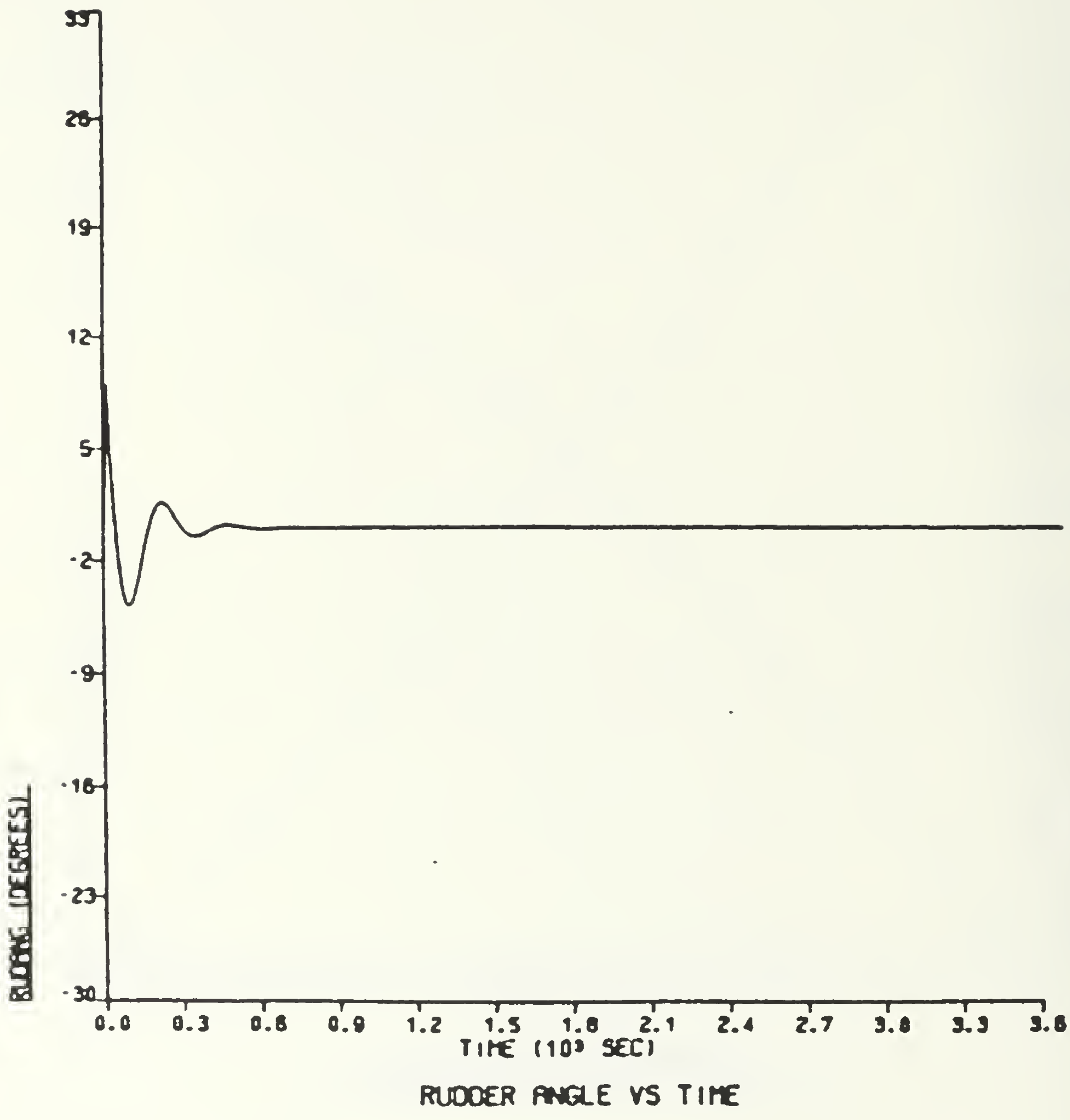

Figure 3.13 Rudder Angle when K4=.01.

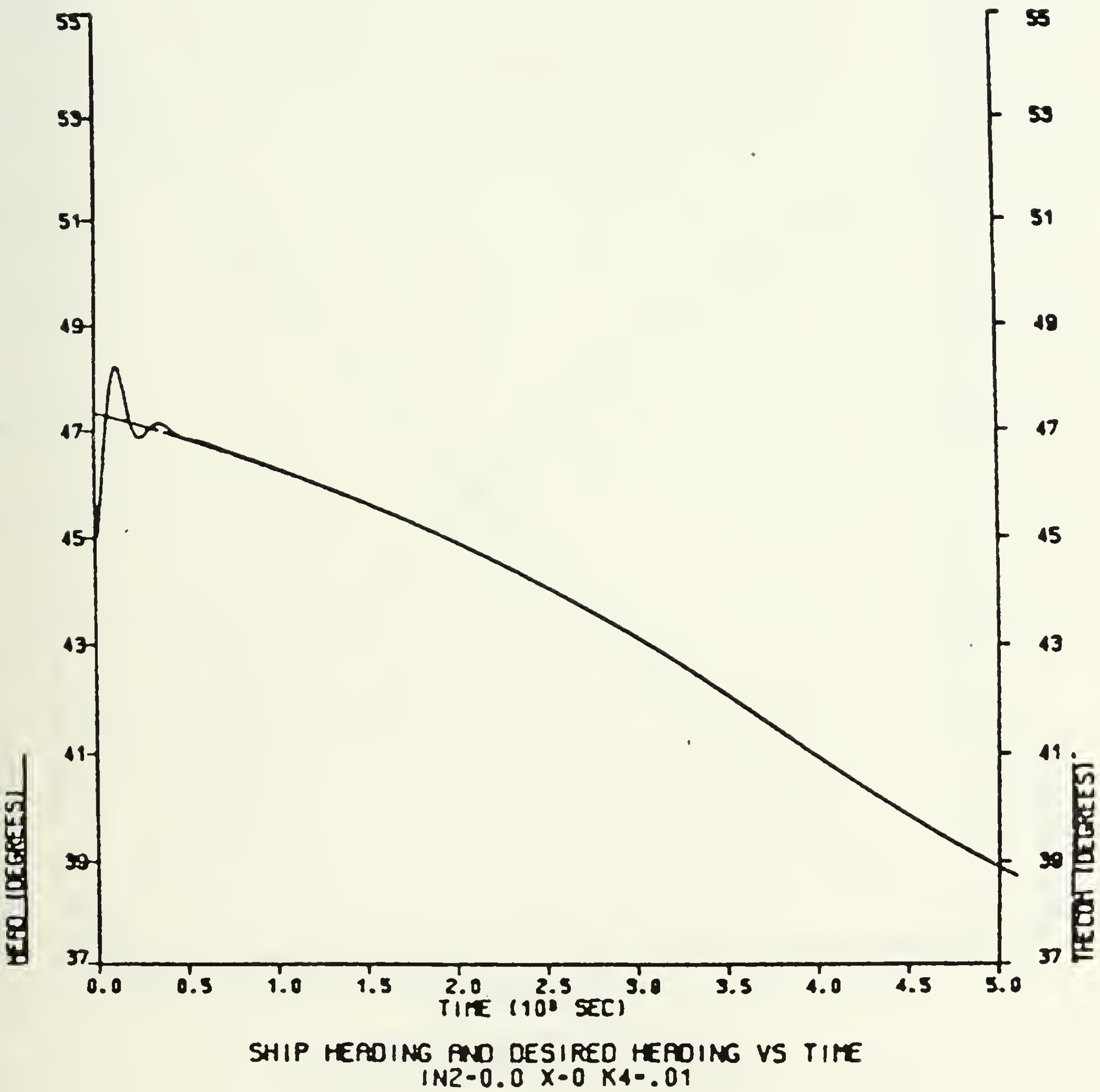

Figure 3.14 Ship Heading and Heading Command when K4=.01.

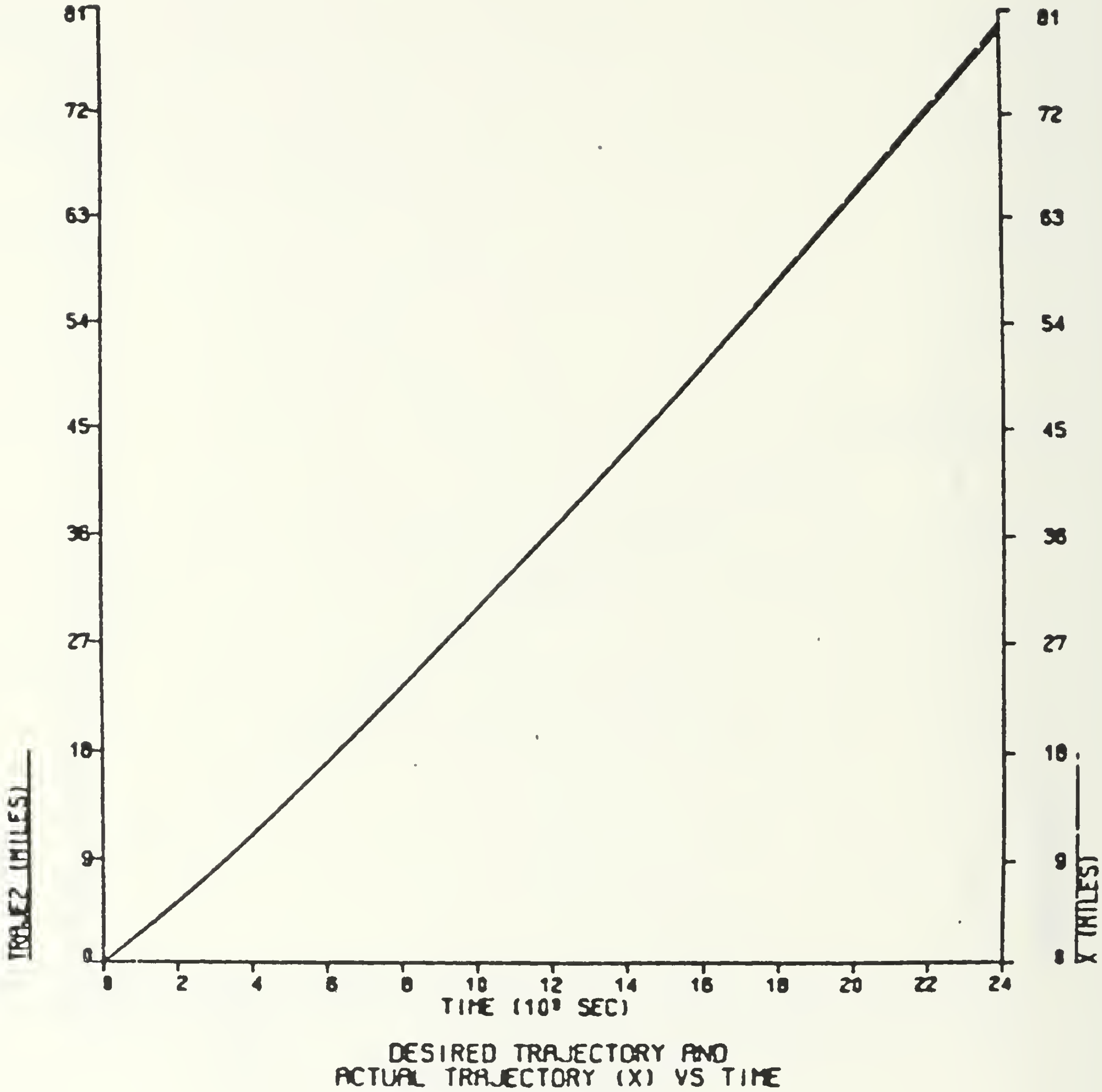

Figure 3.15 Desired Trajectory and X with Disturbance when K4=.01.

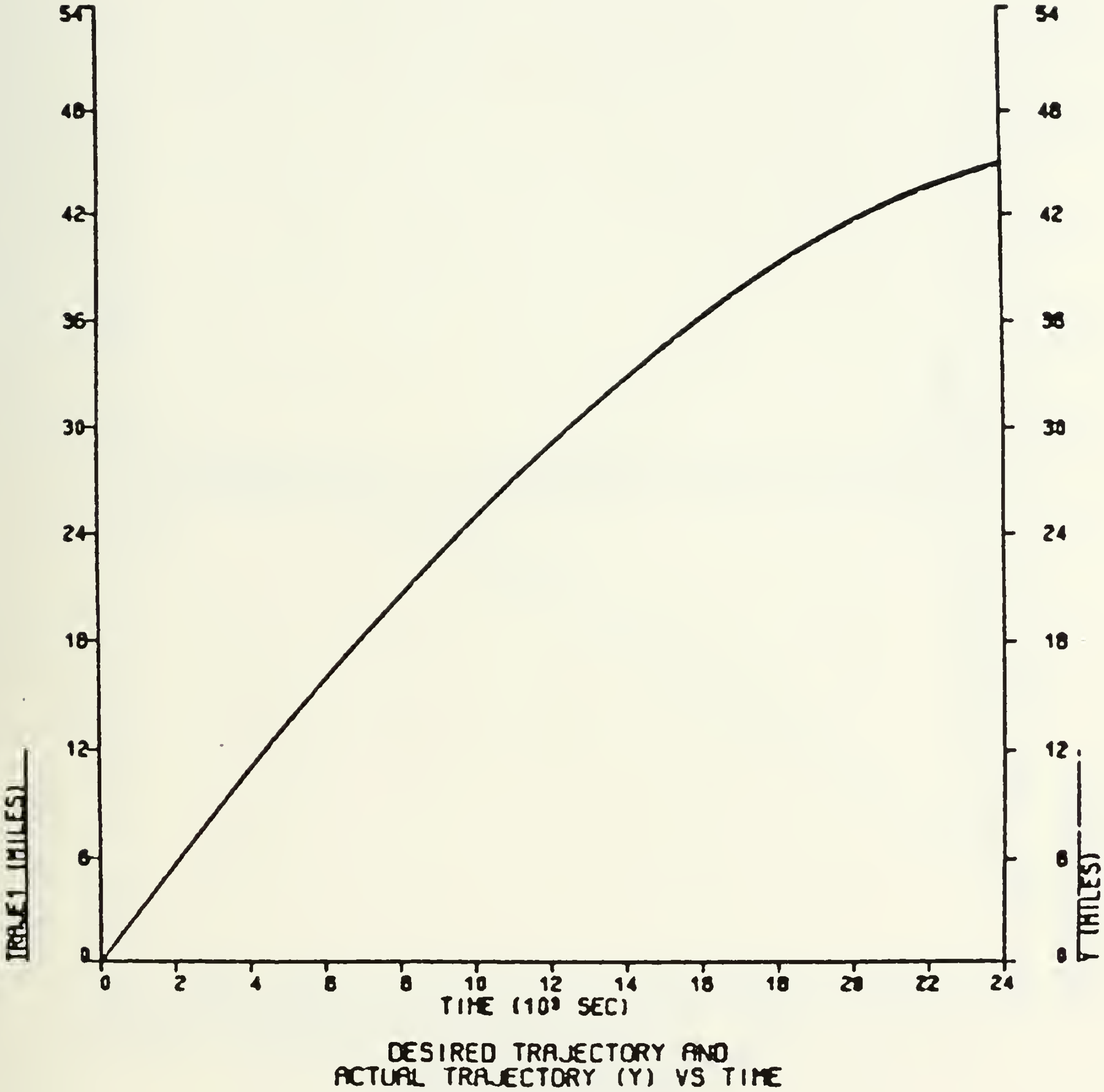

Figure 3.16 Desired Trajectory and Y with Disturbance when K4=.01.

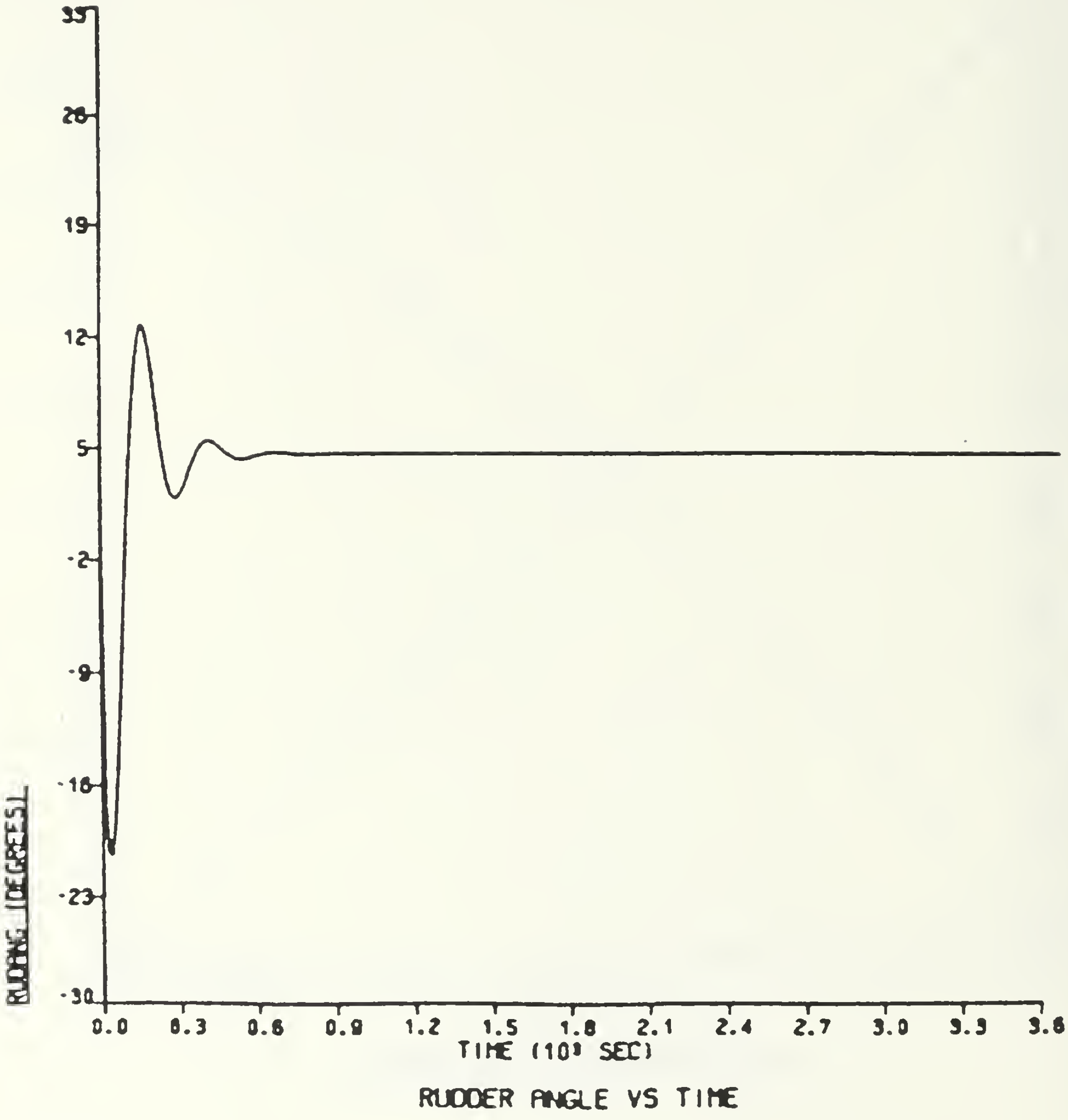

Figure 3.17 Rudder Angle with Disturbance when K4=.01.

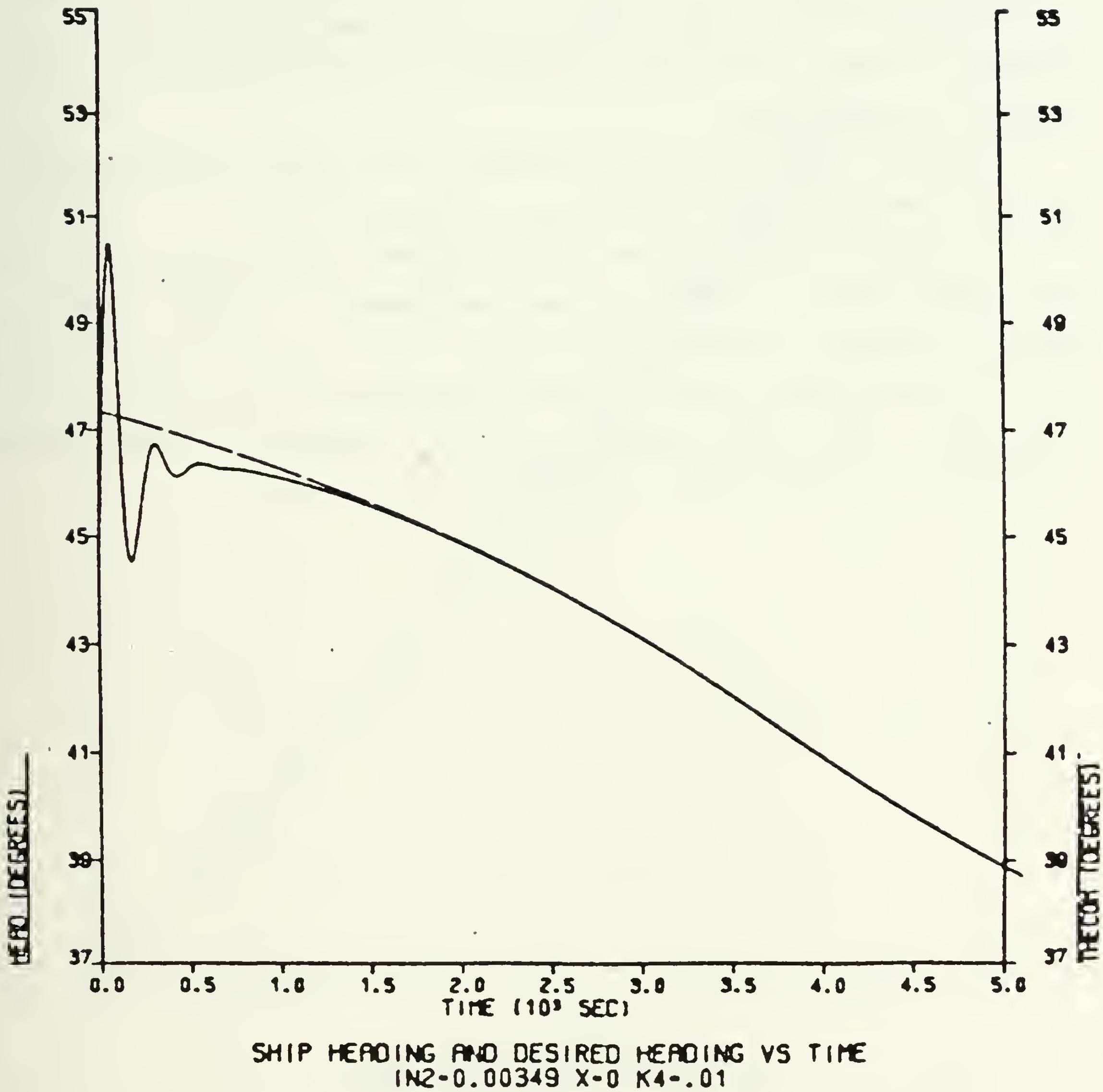

Figure 3.18 Ship Heading and Heading Command with Disturbance when K4 =.01.

Additional simulation runs included disturbances,but it was also assumed that the ship was not on the desired trajectory at the beginning. Figure 3.19-3.22 are the results. In Figure 3.19-3.20,we can notice that the actual trajectory stays away from the desired trajectory all the time,there are no control actions to put the ship back to desired trajectory.

The next step was to include the course correction(O) in the control loop, as shown in Figure 3.23.

Simulations were run with course correction and gain K5,a best value of K5=.75 was obtained. Figure 3.24-3.27 are the results using this value. In Figure 3.24-3.25 the ship comes back to the desired trajectory and follows it all the time. The time from the initial position to the desired trjectory is about 1400 seconds(23.3 minutes).

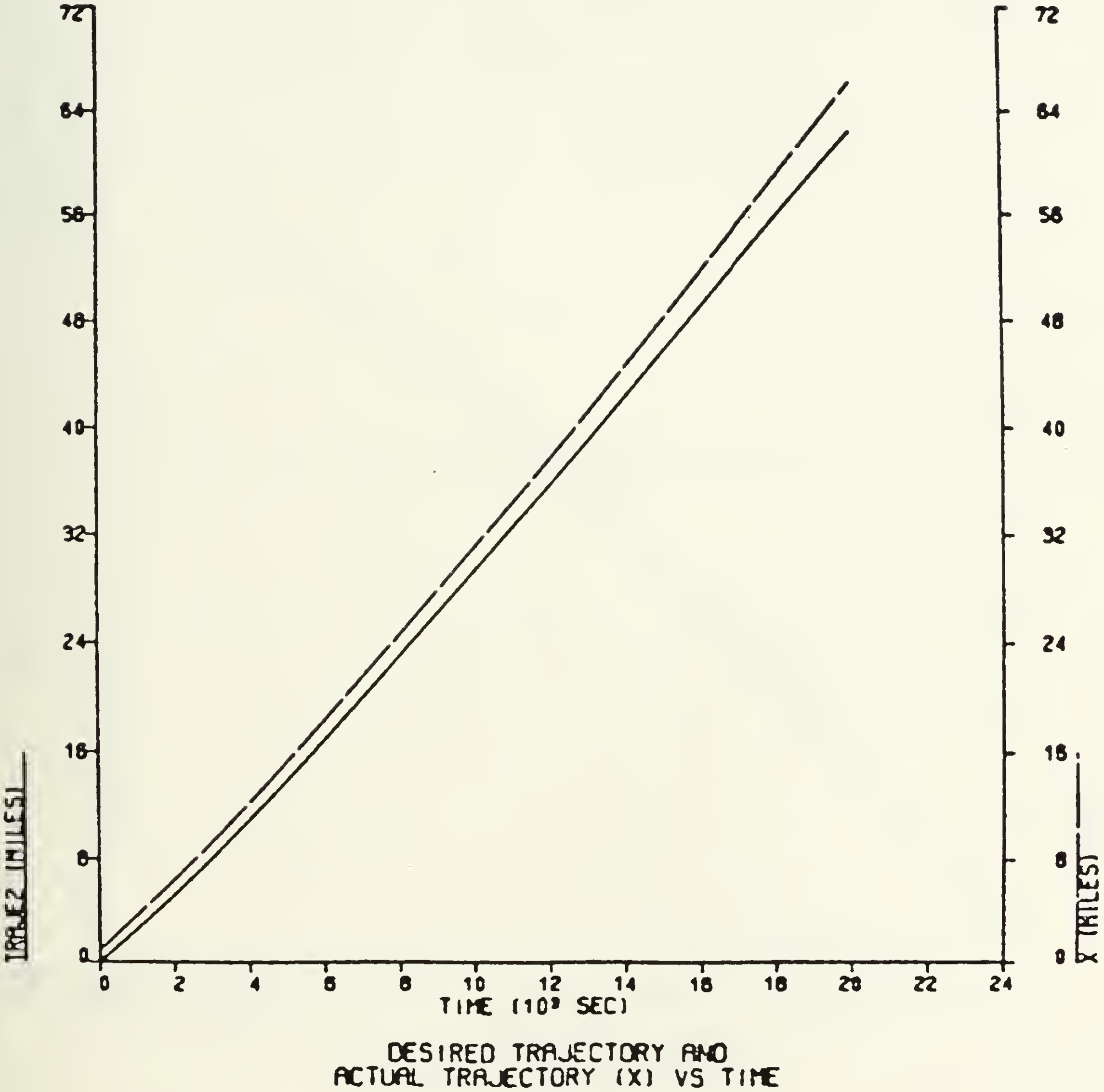

Figure 3.19 Desired Trajectory and X with Initial Value of X=1.

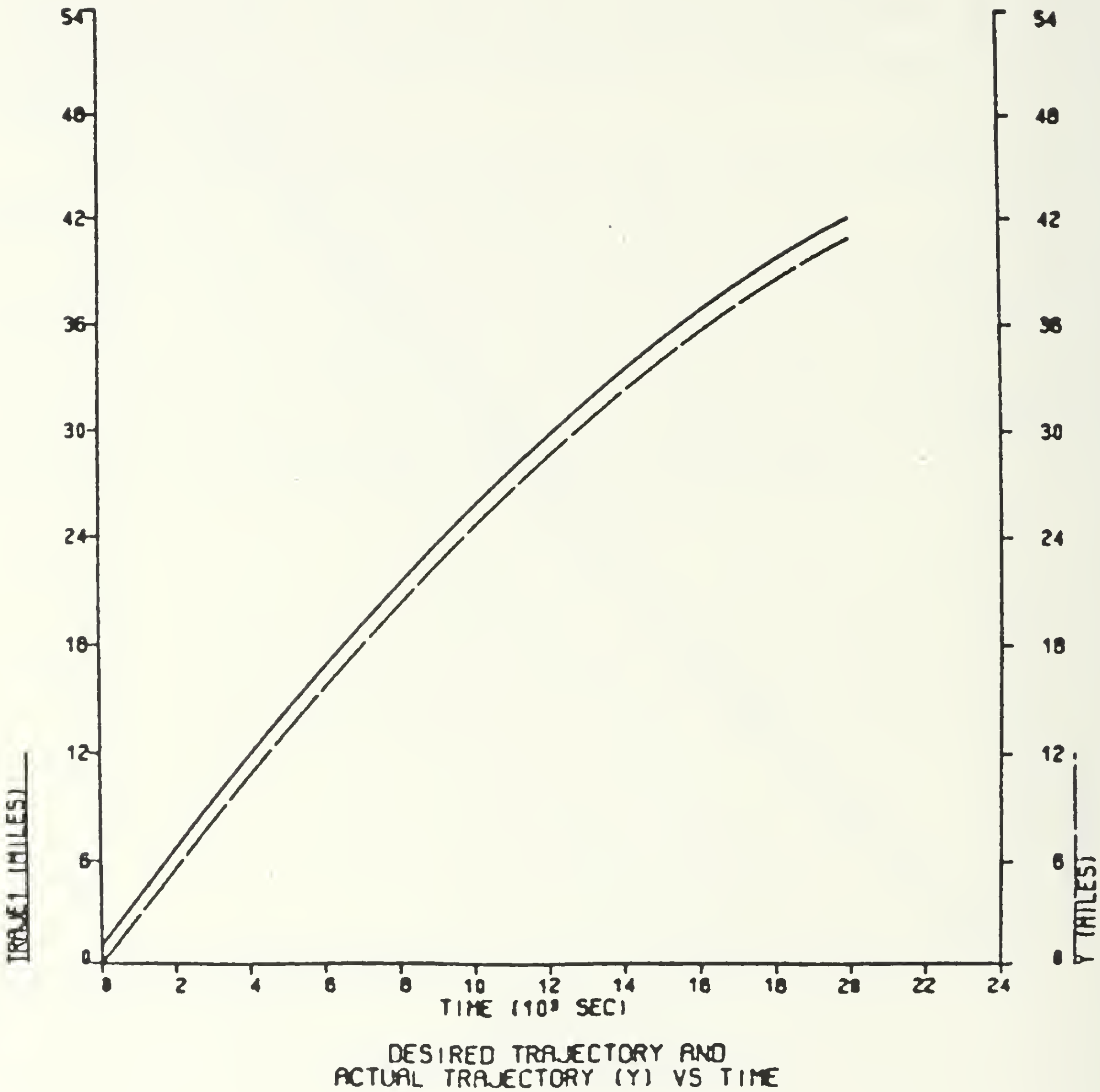

Figure 3.20 Desired Trajectory and Y with Initial Value of x=1.

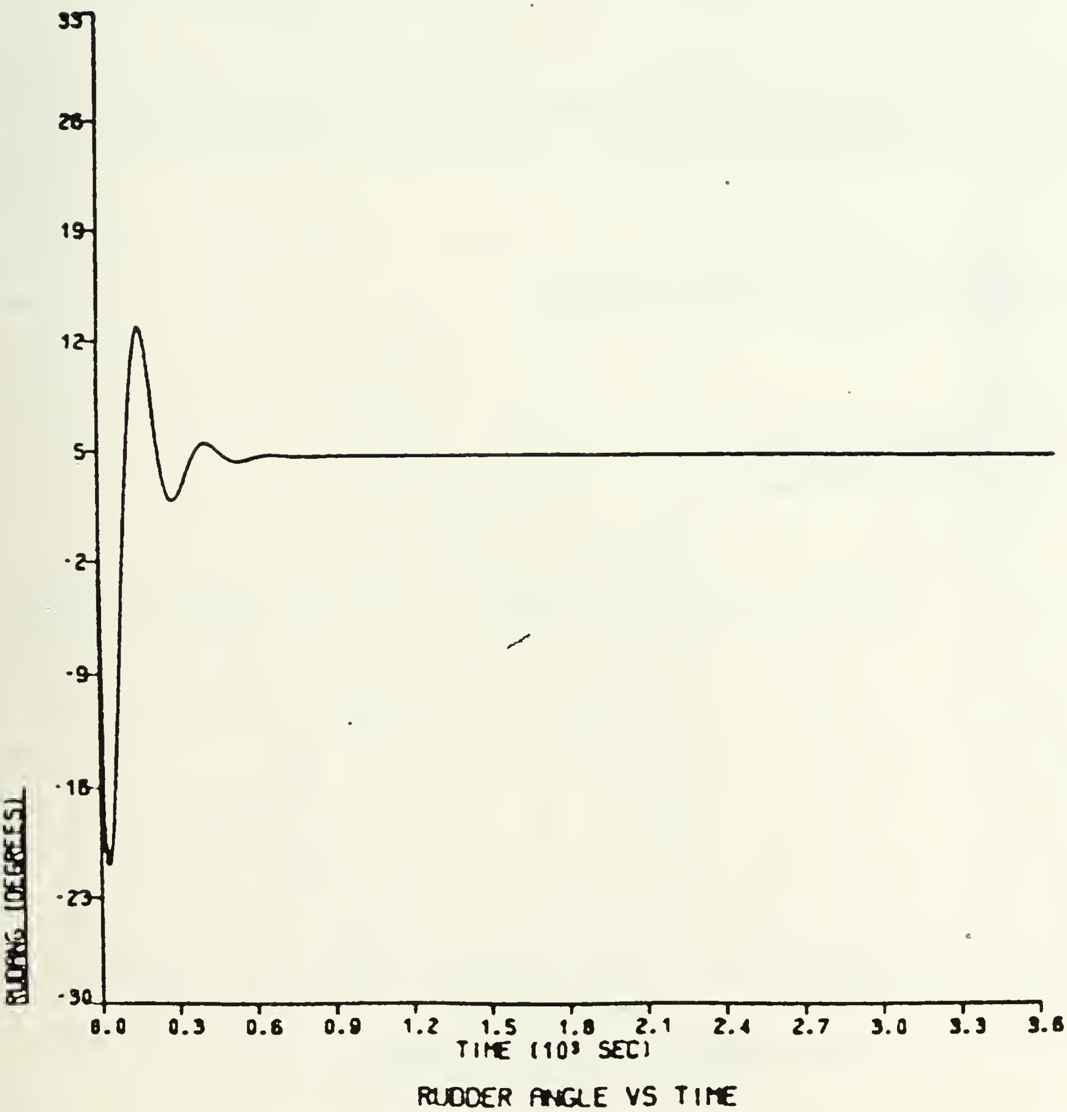

Figure 3.21 Rudder Angle with Initial Value of x=1.

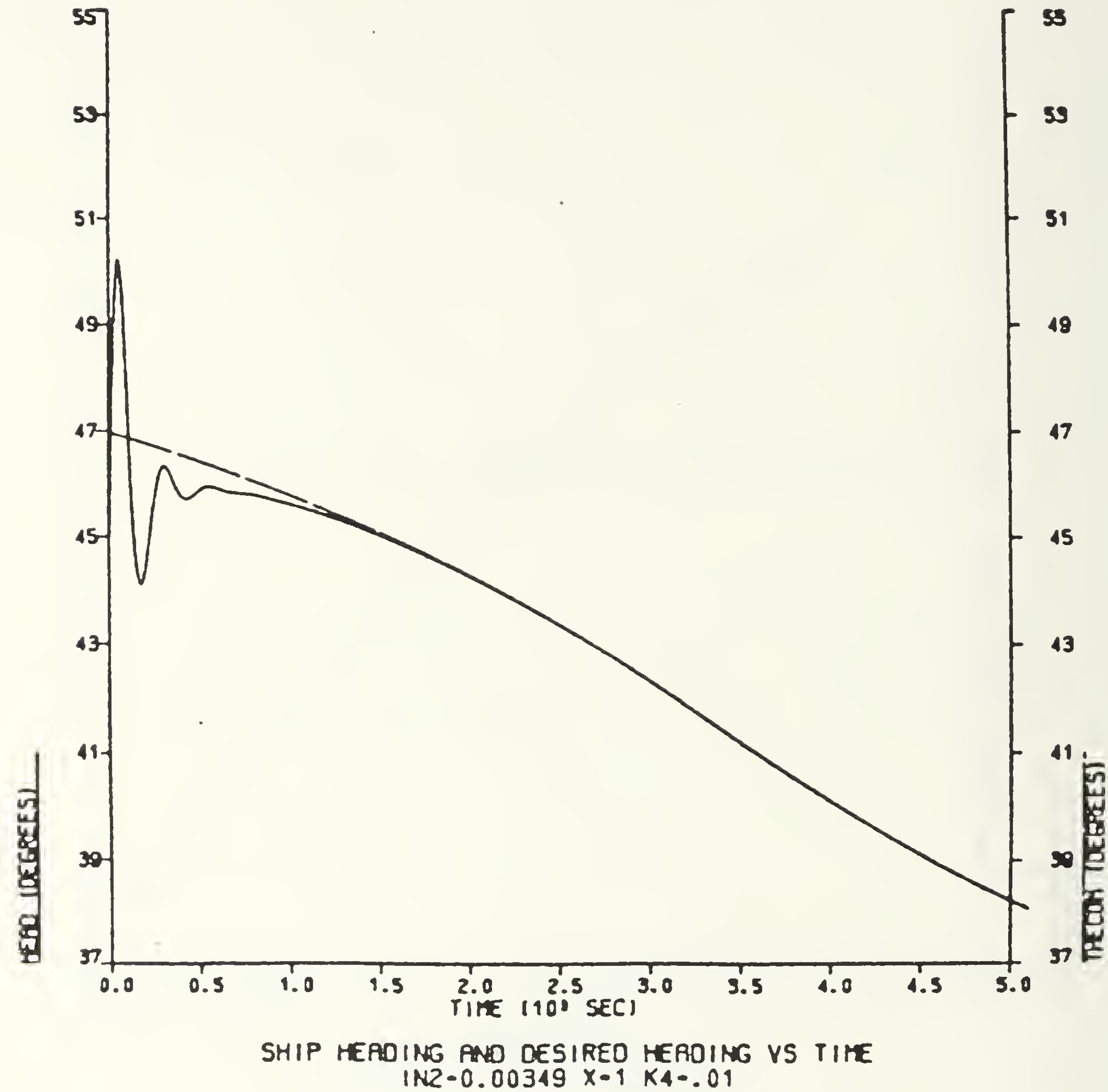

Figure 3.22 Ship Heading and Heading Command with Initial Value of x= 1.

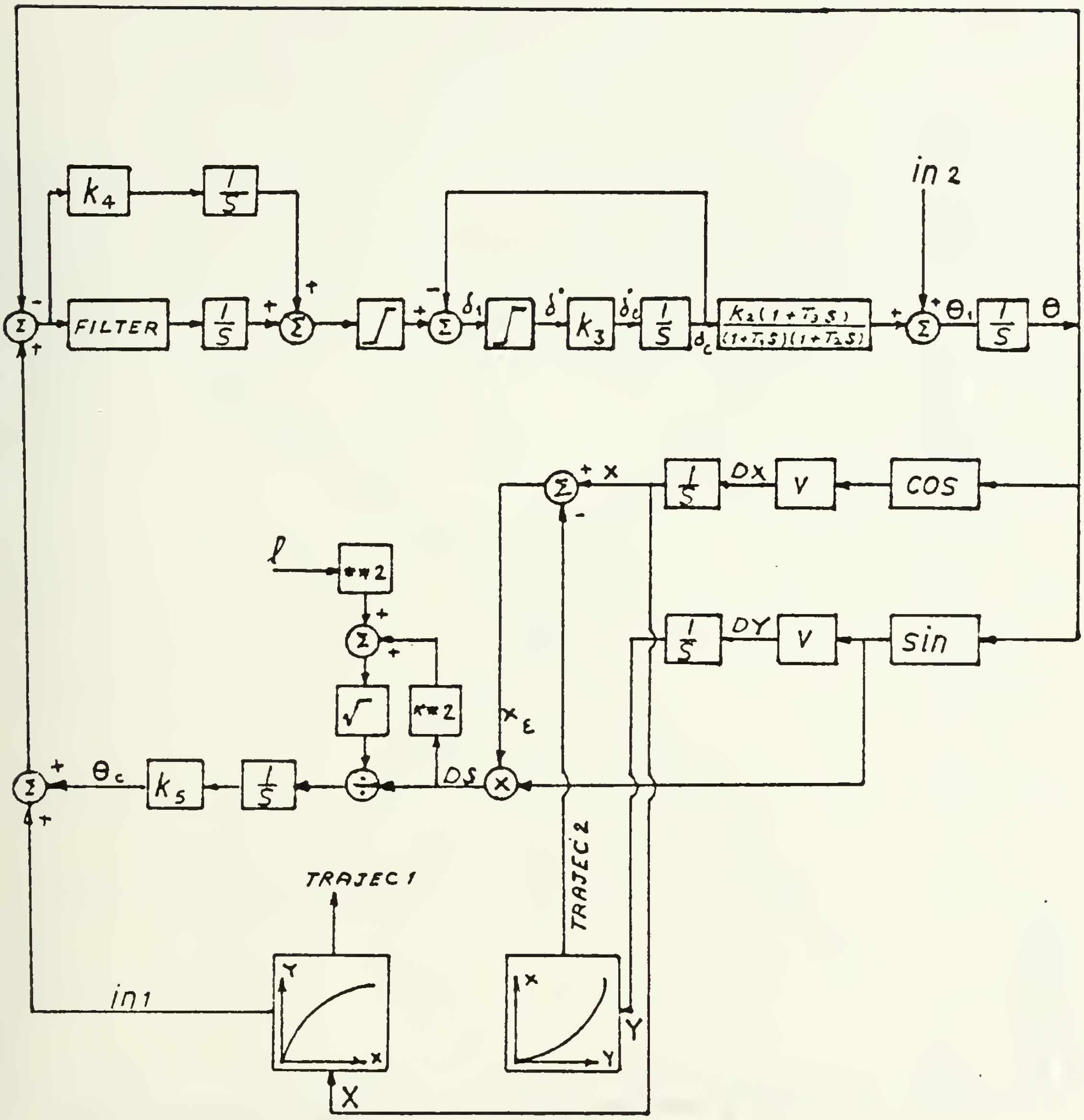

Figure 3.23 The Complete Block Diagram for Course-Keeping and Track-Following.

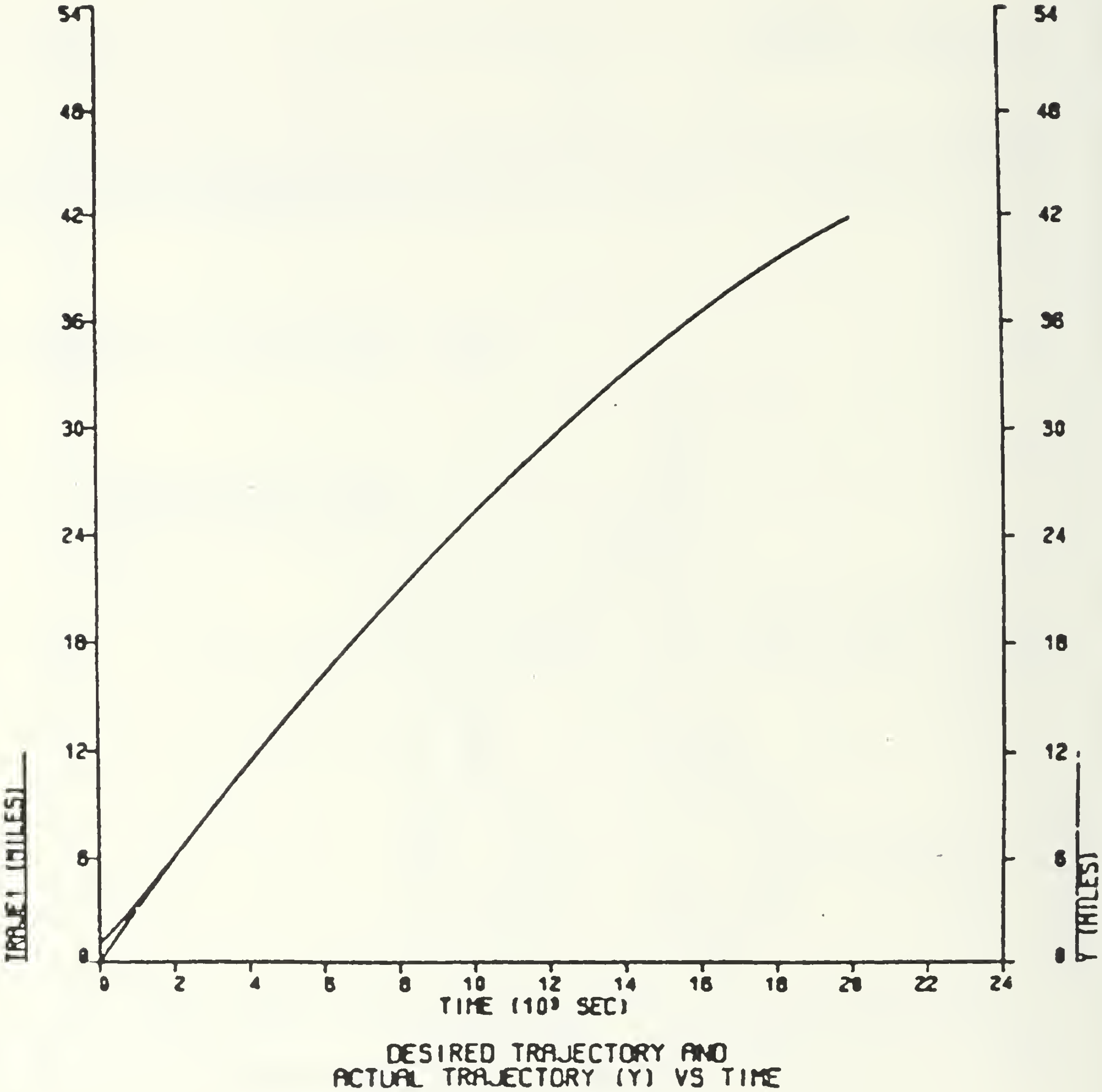

Figure 3.24 Desired Trajectory and Actual Trajectory(y) with K5=.75.

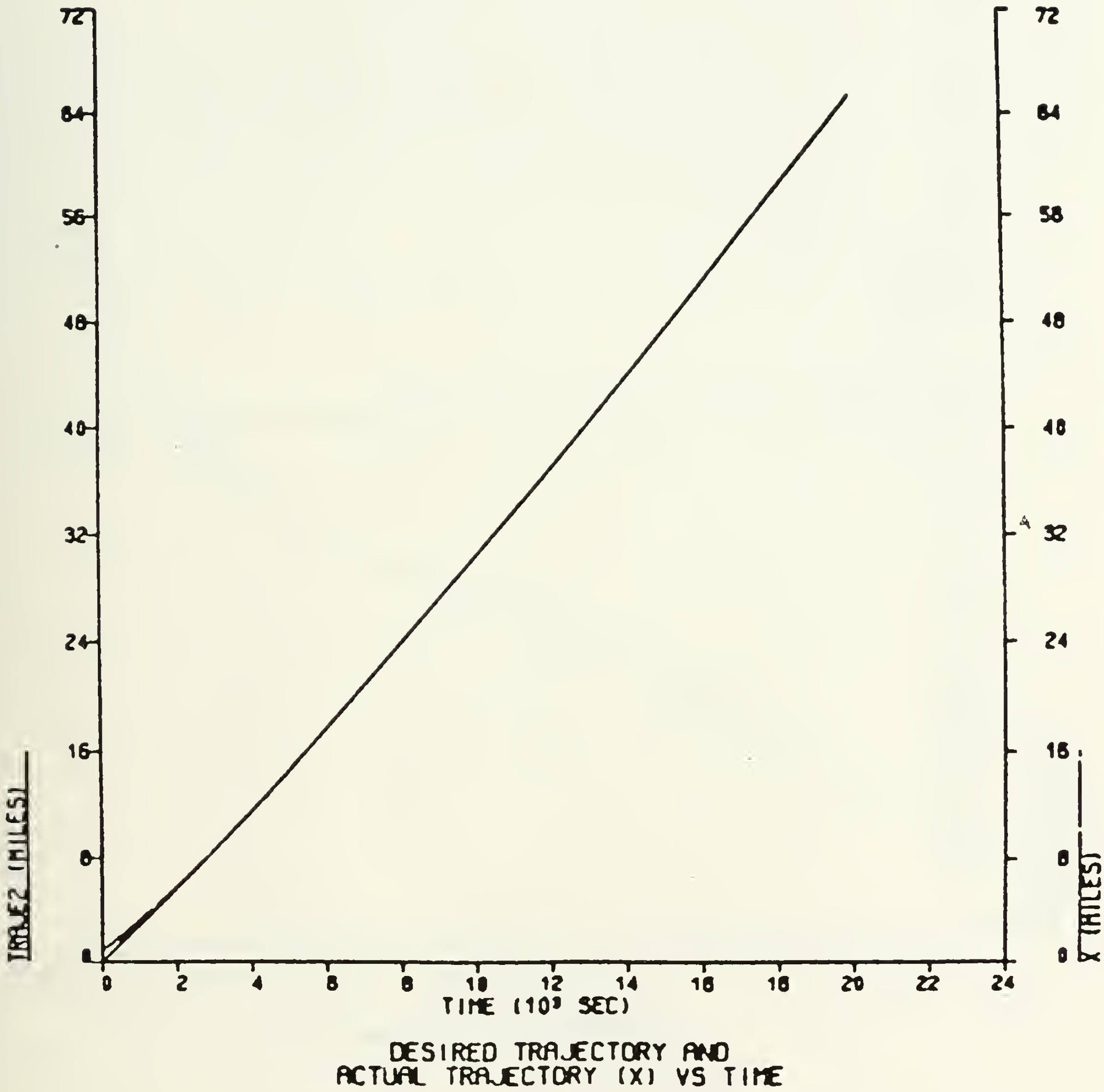

Figure 3.25 Desired Trajectory and Actual Trajectory(x) with K5=.75.

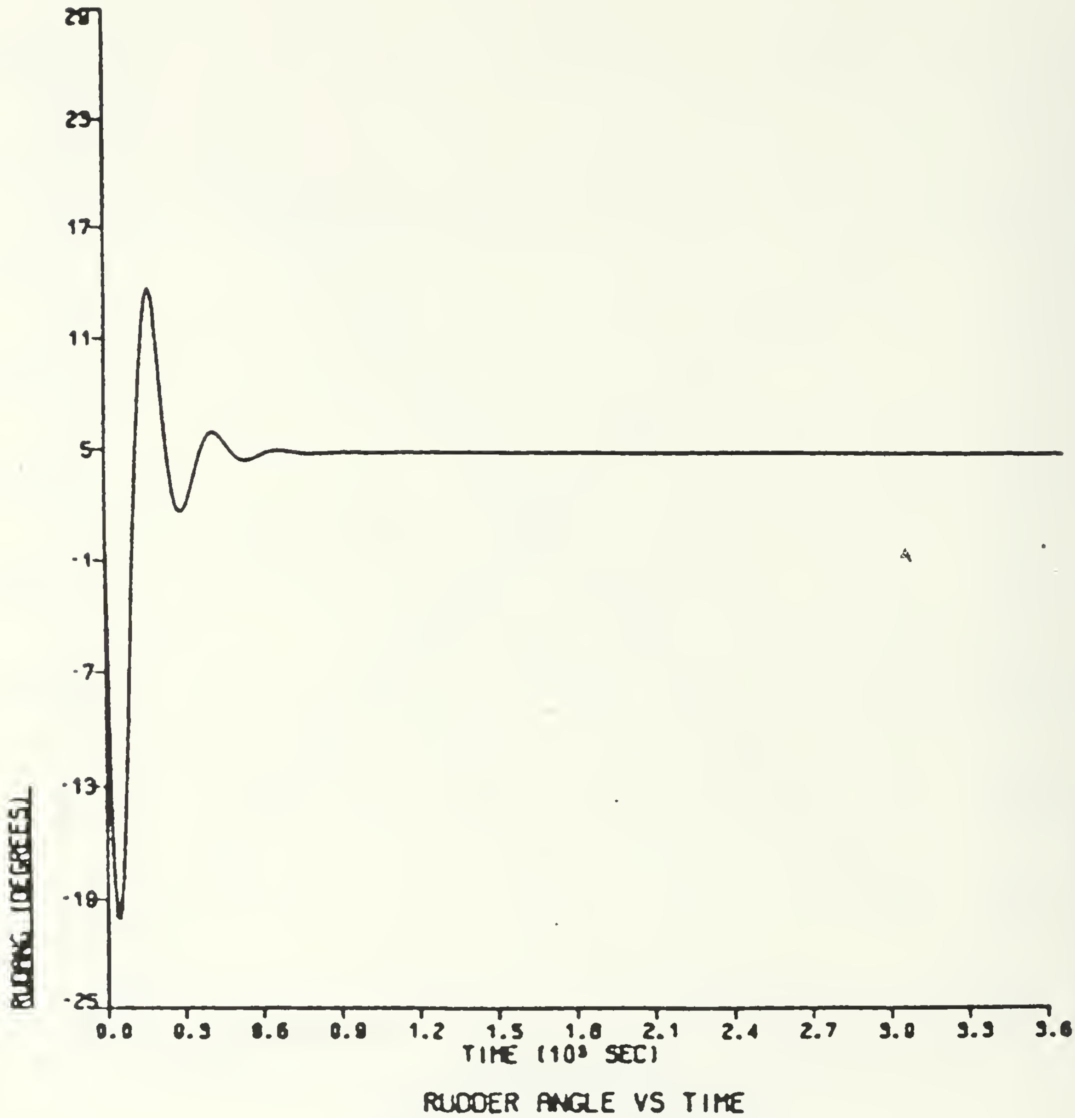

Figure 3.26 Rudder Angle with K5=.75.

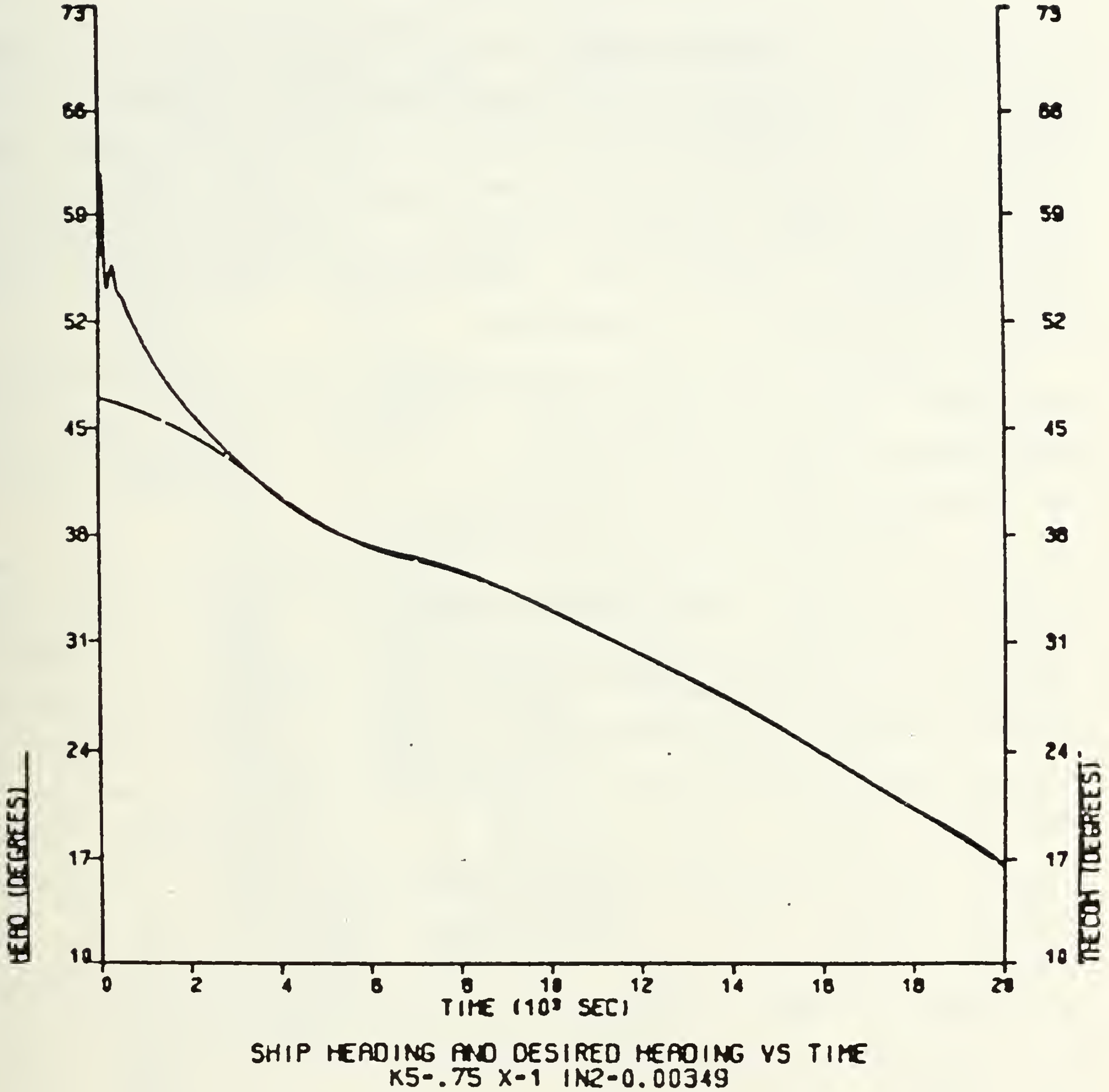

Figure 3.27 Ship Heading and Desired Heading with K=.75.

IV. CONCLUSION

Use of the computer to control the autopilot for both Course-keeping and Track following achieves an accuracy for steady state conditions as high as may be desired. An optimal value of gain for the autopilot was obtained by using the PAROLE program to study families of Root Loci. Both negative and positive feedback can be used,but only negative feedback is recommended.

In Chapter 2 for Course-keeping,the Bode plot is used to show that the filter POLE ZERO and gain were the best for the system. The actual heading in steady state was exactly the desired heading with zero error.

In Chapter 3 the problem of acquiring the track was studied. If the Track following mode is turned on when the ship is many ship lengths off track,the amount of rudder activity is determined by the distance off-track,the nature of the Tracking algorithm,and the shape of track itself,as well as the initial value of the ship heading. It was found that the initial ship heading was important,and rudder activity could be minimized by proper choice of the initial heading angle. This suggests that further study of the effect of initial heading angle is desirable,since manual adjustment of ship heading prior to activating the autopilot could greatly reduce rudder motions. Once the ship reached the track,the system was able to follow the desired trajectory exactly in calm and rough sea.

Further studies may be conducted to include the cost function into these programs to minimize the fuel consumption and to apply optimal control theory to find the optimal track for ship maneuvering at sea.

APPENDIX A

COMPUTER PROGRAM

```
* THIS PROGRAM REFERS TO FIGURES 2.2-2.17
//SOMM07 JOB (2259,1435),'PROJECT',CLASS=B
//*MAIN ORG=NPGVM1.2259P
//*FORMAT PR,DDNAME=PLOTX.SYSVECTR,DEST=LOCAL
//  EXEC DSL
//DSL.INPUT DD *
TITLE AUTOPILOT DESIGN WITHOUT COMPENSATION
INTGER NPLOT
CONST NPLOT=1,IC1=0.,IC2=0.,IC3=0.,IC4=0.,C1=3.1415927
PARAM HEADRF = 10.
PARAM IN2    = 0.0
PARAM G      = 20
PARAM K      = -.0434
PARAM TE     = 1.7
PARAM T1     = -269.3
PARAM T2     = 9.3
PARAM T3     = 20.
DERIVATIVE
      IN1    = HEADRF*C1/180.
      ERROR  = IN1-THETA
      DELTAR = G*ERROR
      DELTA  = REALPL(IC1,TE,DELTAR)
      AMPLI  = K*DELTA
      COMP   = LEDLAG(IC2,T3,T1,AMPLI)
      CORREC = REALPL(IC3,T2,COMP)
      THETA1 = IN2+CORREC
      THETA  = INTGRL(I4,THETA1)
      HEAD   = THETA*180./C1
      RUDANG = DELTA*180./C1
      ERRORD = HEADRF-HEAD
SAMPLE
      CALL DRWG(1,1,TIME,HEAD)
      CALL DRWG(1,2,TIME,HEADRF)
      CALL DRWG(2,1,TIME,RUDANG)
      CALL DRWG(2,2,TIME,HEAD)
TERMINAL
      CALL ENDRW(NPLOT)
PRINT 8.,HEADRF,HEAD,ERRORD,RUDANG
CONTRL FINTIM=800.,DELT=.8,DELS=8.
END
STOP
//PLOT.PLOTPARM DD *
 &PLOT SCALE=.65 &END
//PLOT.SYSIN DD *
HEAD AND HEADRF VS TIME
HEADRF=10 IN2=0.0 G=20
RUDDER ANGLE AND HEAD VS TIME
HEADRF=10 IN2=0.0 G=20
/*
/*
```

FILE: EE44181 DSL A1

```
* THIS PROGRAM REFERS TO FIGURES 2.21-2.24
//SOMMAR3 JOB (2259,1435),'EE44181',CLASS=B
//*MAIN ORG=NPGVM1.2259P,LINES=(10)
//*FORMAT PR,DDNAME=PLOTX.SYSVECTR,DEST=LOCAL
//  EXEC DSL
//DSL.INPUT DD *
TITLE AUTOPILOT DESIGN WITH COMPENSATION
INTGER NPLOT
CONST NPLOT=4,IC1=0.,IC2=0.,IC3=0.,IC4=0.,C1=3.1415927
PARAM HEADRF=0.
PARAM IN2=0.00349
PARAM G=3.5
PARAM K=-.0434
PARAM TE=1.7
PARAM T1=-269.3
PARAM T2=9.3
PARAM T3=20.
DERIVATIVE
      IN1    = HEADRF*C1/180.
      ERROR  = IN1-THETA
      FILTER = LEDLAG(0.,25.,2.5,ERROR)
      DELTAR = G*FILTER
      DELTA  = REALPL(IC1,TE,DELTAR)
      AMPLI  = K*DELTA
      COMP   = LEDLAG(IC2,T3,T1,AMPLI)
      CORREC = REALPL(IC3,T2,COMP)
      THETA1 = IN2+CORREC
      THETA  = INTGRL(I4,THETA1)
      HEAD   = THETA*180./C1
      RUDANG = DELTA*180./C1
      ERRORD = HEADRF-HEAD
SAMPLE
      CALL DRWG(1,1,TIME,RUDANG)
      CALL DRWG(1,2,TIME,HEAD)
TERMINAL
      CALL ENDRW(NPLOT)
PRINT 3.,HEAD,RUDANG
CONTRL FINTIM=800.,DELT=.8,DELS=8.
END
PARAM G=10
END
PARAM G=15
END
PARAM G=24.2
END
STOP
//PLOT.PLOTPARM DD *
 &PLOT SCALE=.65 &END
//PLOT.SYSIN DD *
RUDDER ANGLE AND HEAD VS TIME
SOMMART G=3.5 IN2=.00349
RUDDER ANGLE AND HEAD VS TIME
SOMMART G=10 IN2=.00349
RUDDER ANGLE AND HEAD VS TIME
SOMMART G=15 IN2=.00349
```

FILE: EE44185 DSL A1

```
* THIS PROGRAM REFERS TO FIGURES 2.27-2.33
//SOMMAR7 JOB (2259,1435),'EE44184',CLASS=B
//*MAIN ORG=NPGVM1.2259P,LINES=(10)
//*FORMAT PR,DDNAME=PLOTX.SYSVECTR,DEST=LOCAL
// EXEC DSL
//DSL.INPUT DD *
TITLE AUTOPILOT DESIGN WITH COMPENSATION AND LIMITER
PARAM IN2=0.00349
PARAM K1=24.2
PARAM K2=-.0434,K3=.588,...
      P1=-.1222,P2=.1222,P3=-.52,P4=.52,K4=0.0
PARAM HEADRF=3
INTGER NPLOT
CONST NPLOT=1,C1=3.1415927
DERIVATIVE
      IN1    = HEADRF*C1/180.
      ERROR1 = IN1-THETA
      FILTER = LEDLAG(0.,25.,2.5,ERROR1)
      DELREF = FILTER*K1
      DELDES = LIMIT(P3,P4,DELREF)
      DELTA1 = DELDES-DELTAC
      DELDOT = LIMIT(P1,P2,DELTA1)
      DELDOC = K3*DELDOT
      DELTAC = INTGRL(0.,DELDOC)
      AMPLI  = K2*DELTAC
      COMP   = LEDLAG(0.,20.,-269.3,AMPLI)
      CORREC = REALPL(0.,9.3,COMP)
      THETA1 = IN2+CORREC
      THETA  = INTGRL(0.,THETA1)
      RUDANG = DELTAC*180./C1
      HEAD   = THETA*180./C1
      ERRORD = HEADRF-HEAD
SAMPLE
      CALL DRWG(1,1,TIME,RUDANG)
      CALL DRWG(1,2,TIME,HEAD)
TERMINAL
      CALL ENDRW(NPLOT)
PRINT 8.,RUDANG,HEAD,ERRORD
CONTRL FINTIM=700.,DELT=.7,DELS=7.
INTEG RKSFX
END
STOP
//PLOT.PLOTPARM DD *
 &PLOT SCALE=.65 &END
//PLOT.SYSIN DD *
RUDDER ANGLE & HEAD VS TIME
IN2=0.00349 K1=24.2 HEADRF=3
/*
/*
```

FILE: T2 DSL A1

```
* THIS PROGRAM REFERS TO FIGURES 3.3-3.4
//SOMMA21 JOB (2259,1435),'PROJECT',CLASS=B
//*MAIN ORG=NPGVM1.2259P,LINES=(10)
//*FORMAT PR,DDNAME=PLOTX.SYSVECTR,DEST=LOCAL
// EXEC DSL
//DSL.INPUT DD *
TITLE SIMULATION OF SHIP DYNAMICS (TEST OF FOLLOWING)
PARAM K1=4.6,K2=-.0434,K3=.588,...
      P1=-.1222,P2=.1222,P3=-.52,P4=.52
PARAM V=0.0038889
* SPEED IN MILES/SECOND WHICH IS EQUIVALENT TO 14 KNOTS
PARAM IN2=0.0,HEADRF=5
CONST NPLOT=1,C1=3.1415927
INTGER NPLOT
DERIVATIVE
      IN1    = HEADRF*C1/180.
      E1     = IN1-THETA
      FILTER= LEDLAG(0.,25.,2.5,E1)
      E2     = FILTER*K1
      E3     = E1*K4
      E4     = INTGRL(0.,E3)
      DELREF= E2+E4
      DELDES= LIMIT(P3,P4,DELREF)
      DELTA1= DELDES-DELTAC
      DELDOT= LIMIT(P1,P2,DELTA1)
      DELDOC= K3*DELDOT
      DELTAC= INTGRL(0.,DELDOC)
      AMPLI = K2*DELTAC
      COMP   = LEDLAG(0.,20.,-269.3,AMPLI)
      CORREC= REALPL(0.,9.3,COMP)
      THETA1= IN2+CORREC
      THETA = INTGRL(0.,THETA1)
      HEAD   = THETA *180./C1
      RUDANG= DELTAC*180./C1
      DX     = V*COS(THETA)
      DY     = V*SIN(THETA)
      X      = INTGRL(0.,DX)
      Y      = INTGRL(0.,DY)
SAMPLE
      CALL DRWG(1,1,TIME,HEAD)
      CALL DRWG(1,2,TIME,HEADRF)
      CALL DRWG(2,1,TIME,X)
      CALL DRWG(2,2,TIME,Y)
TERMINAL
      CALL ENDRW(NPLOT)
PRINT 8.,HEAD,HEADRF,X,Y
CONTRL FINTIM=650.,DELT=.4,DELS=.65
INTEG  RKSFX
END
STOP
//PLOT.PLOTPARM DD *
 &PLOT SCALE=.65 &END
//PLOT.SYSIN DD *
HEAD AND HEADRF VS TIME
HEADRF=5 IN2=0
```

```
FILE: SOM2     DSL      A1

* THIS PROGRAM REFERS TO FIGURES 3.11-3.22
TITLE SIMULATION OF SHIP DYNAMICS (TEST OF FOLLOWING)
PARAM K1=4.6,K2=-.0434,K3=.588,K4=0.01,...
      P1=-.1222,P2=.1222,P3=-.52,P4=.52
PARAM V=0.0038889
* SPEED IN MILES/SECOND WHICH IS EQUIVALENT TO 14 KNOTS
PARAM EPSILX=0.125,G=-.074
PARAM IN2=0.00349
CONST C1=3.1415927
NLFGEN YPATH=-20.,-30.,-10.,-12.5,0.,0.,10.,10.,20.,...
 18.,30.,25.,40.,31.,50.,36.,60.,40.,70.,43.,80.,...
 45.,90.,46.5,100.,48.
NLFGEN XPATH=-30.,-20.,-12.5,-10.,0.,0.,10.,10.,18.,...
 20.,25.,30.,31.,40.,36.,50.,40.,60.,43.,70.,45.,...
 80.,46.5,90.,48.,100.
DYNAMIC
      TRAJE1 = NLFGEN(YPATH,X)
      TRAJE2 = NLFGEN(XPATH,Y)
      DELTAX = (X+EPSILX)-X
      DELTAY = NLFGEN(YPATH,X+EPSILX)-NLFGEN(YPATH,X)
      Z      = DELTAY/DELTAX
      ZR     = ATAN(Z)
      THECOM = ZR*180./C1
DERIVATIVE
      IN1    = THECOM*C1/180.
      E      = IN1-THETA
      E1     = 10.*E
      FILTER = ZEROPL(0.,.04,0.4,E1)
      E2     = FILTER*K1
      E3     = E*K4
      E4     = INTGRL(0.,E3)
      DELREF = E2+E4
      DELDES = LIMIT(P3,P4,DELREF)
      DELTA1 = DELDES-DELTAC
      DELDOT = LIMIT(P1,P2,DELTA1)
      DELDOC = K3*DELDOT
      DELTAC = INTGRL(0.,DELDOC)
      AMPLI1 = K2*DELTAC
      AMPLI  = G*AMPLI1
      COMP   = ZEROPL(0.,.05,-.0037,AMPLI)
      CORREC = REALPL(0.,9.3,COMP)
      THETA1 = IN2+CORREC
      THETA2 = INTGRL(0.7853982,THETA1)
 PROCED THETA = COR(THETA2,C1)
      THETA3 = THETA2
  3   IF(ABS(THETA3).LT.C1) GO TO 5
      IF(THETA3.LT.0) GO TO 4
      THETA3 = THETA2-C1
      GO TO 3
  4   THETA3 = THETA2+C1
      GO TO 3
  5   THETA  = THETA2
 ENDPRO
      HEAD   = THETA *180./C1
      RUDANG = DELTAC*180./C1
```

FILE: SOM2 DSL A1

```
      DX     = V*COS(THETA)
      DY     = V*SIN(THETA)
      X      = INTGRL(0.,DX)
      Y      = INTGRL(0.,DY)
PRINT 125.,RUDANG,HEAD,THECOM,X,TRAJE1,Y,TRAJE2
CONTRL FINTIM=24000.,DELT=6.,DELS=20.
SAVE  (G1)12.,HEAD,THECOM
SAVE  (G2)12.,TRAJE1,Y
SAVE  (G3)12.,TRAJE2,X
SAVE  (G4)12.,RUDANG
GRAPH (G1/G1,DE=TEK618,PO=0,.5) TIME(LE=8.0,SC=500.,...
      NI=10,UN='SEC'),...
      HEAD(LE=9,NI=9,LO=37,SC=2.,UN='DEGREES'),...
      THECOM(LE=9,NI=9,PO=8.,LO=37,SC=2.,UN='DEGREES')
GRAPH (G2/G2,DE=TEK618,PO=0,.5) TIME(LE=8.,SC=2000.,...
      NI=12,UN='SEC'),...
      TRAJE1(LE=9,NI=9,LO=0,SC=6.,UN='MILES'),...
      Y(LE=9,NI=9,PO=8.,LO=0,SC=6.,UN='MILES')
GRAPH (G3/G3,DE=TEK618,PO=0,.5) TIME(LE=8.,SC=2000.,...
      NI=12,UN='SEC'),...
      TRAJE2(LE=9,NI=9,LO=0,SC=9.,UN='MILES'),...
      X(LE=9,NI=9,PO=8.,LO=0,SC=9.,UN='MILES')
GRAPH (G4/G4,DE=TEK618) TIME(LE=8.,SC=300.,...
      NI=12,UN='SEC'),...
      RUDANG(LE=9,NI=9,LO=-30,SC=7.,UN='DEGREES')
LABEL (G1) SHIP HEADING AND DESIRED HEADING VS TIME
LABEL (G1) IN2=0.00349 X=0 K4=.01
LABEL (G2) DESIRED TRAJECTORY AND
LABEL (G2) ACTUAL TRAJECTORY (Y) VS TIME
LABEL (G3) DESIRED TRAJECTORY AND
LABEL (G3) ACTUAL TRAJECTORY (X) VS TIME
LABEL (G4) RUDDER ANGLE VS TIME
END
STOP
```

```
FILE: SOM1     DSL      A1


* THIS PROGRAM REFERS TO FIGURE 3.24 TO 3.27
TITLE SIMULATION OF SHIP DYNAMICS (TEST OF FOLLOWING)
PARAM K1=4.6,K2=-.0434,K3=.588,K4=0.01,K5=0.75,...
      P1=-.1222,P2=.1222,P3=-.52,P4=.52
PARAM V=0.0038889
* SPEED IN MILES/SECOND WHICH IS EQUIVALENT TO 14 KNOTS
PARAM EPSILX=0.125,G=-.074
PARAM L=2.5,IN2=0.00349
CONST C1=3.1415927
NLFGEN YPATH=-20.,-30.,-10.,-12.5,0.,0.,10.,10.,20.,...
 18.,30.,25.,40.,31.,50.,36.,60.,40.,70.,43.,...
 80.,45.,90.,46.5,100.,48.
NLFGEN XPATH=-30.,-20.,-12.5,-10.,0.,0.,10.,10.,18.,...
 20.,25.,30.,31.,40.,36.,50.,40.,60.,43.,70.,...
 45.,80.,46.5,90.,48.,100.
DYNAMIC
      TRAJE1 = NLFGEN(YPATH,X)
      TRAJE2 = NLFGEN(XPATH,Y)
      DELTAX = (X+EPSILX)-X
      DELTAY = NLFGEN(YPATH,X+EPSILX)-NLFGEN(YPATH,X)
      Z      = DELTAY/DELTAX
      ZR     = ATAN(Z)
      THECOM = ZR*180./C1
DERIVATIVE
      IN1    = THECOM*C1/180.
      E      = IN1-THETA+THETAC
      E1     = 10.*E
      FILTER = ZEROPL(0.,.04,0.4,E1)
      E2     = FILTER*K1
      E3     = E*K4
      E4     = INTGRL(0.,E3)
      DELREF = E2+E4
      DELDES = LIMIT(P3,P4,DELREF)
      DELTA1 = DELDES-DELTAC
      DELDOT = LIMIT(P1,P2,DELTA1)
      DELDOC = K3*DELDOT
      DELTAC = INTGRL(0.,DELDOC)
      AMPLI1 = K2*DELTAC
      AMPLI  = G*AMPLI1
      COMP   = ZEROPL(0.,.05,-.0037,AMPLI)
      CORREC = REALPL(0.,9.3,COMP)
      THETA1 = IN2+CORREC
      THETA2 = INTGRL(0.9599311,THETA1)
 PROCED THETA = COR(THETA2,C1)
      THETA3 = THETA2
  3   IF(ABS(THETA3).LT.C1) GO TO 5
      IF(THETA3.LT.0) GO TO 4
      THETA3 = THETA2-C1
      GO TO 3
  4   THETA3 = THETA2+C1
      GO TO 3
  5   THETA  = THETA2
 ENDPRO
      HEAD   = THETA *180./C1
      RUDANG = DELTAC*180./C1
```

```
FILE: SOM1     DSL      A1

      DX     = V*COS(THETA)
      DY     = V*SIN(THETA)
      X      = INTGRL(1.,DX)
      Y      = INTGRL(0.,DY)
      YERROR = TRAJE1-Y
      XERROR = X-TRAJE2
      DS     = XERROR*SIN(IN1)
      N      = DS**2+L**2
      P      = SQRT(N)
      M      = DS/P
      THETC1 = ASIN(M)
      THETAC = K5*THETC1
      T      = THETAC*180./C1
PRINT 125.,RUDANG,HEAD,THECOM,X,TRAJE1,Y,TRAJE2,DS
CONTRL FINTIM=20000.,DELT=6.,DELS=20.
SAVE  (G1)12.,HEAD,THECOM
SAVE  (G2)12.,TRAJE1,Y
SAVE  (G3)12.,TRAJE2,X
SAVE  (G4)12.,RUDANG
GRAPH (G1/G1,DE=TEK618,PO=0,.5) TIME(LE=8.0,SC=2000.,...
      NI=10,UN='SEC'),...
      HEAD(LE=9,NI=9,LO=10,SC=7.,UN='DEGREES'),...
      THECOM(LE=9,NI=9,PO=8.,LO=10,SC=7.,UN='DEGREES')
GRAPH (G2/G2,DE=TEK618,PO=0,.5) TIME(LE=8.,SC=2000.,...
      NI=12,UN='SEC'),...
      TRAJE1(LE=9,NI=9,LO=0,SC=6.,UN='MILES'),...
      Y(LE=9,NI=9,PO=8.,LO=0,SC=6.,UN='MILES')
GRAPH (G3/G3,DE=TEK618,PO=0,.5) TIME(LE=8.,SC=2000.,...
      NI=12,UN='SEC'),...
      TRAJE2(LE=9,NI=9,LO=0,SC=8.,UN='MILES'),...
      X(LE=9,NI=9,PO=8.,LO=0,SC=8.,UN='MILES')
GRAPH (G4/G4,DE=TEK618,PO=0,.5) TIME(LE=8.,SC=300.,...
      NI=12,UN='SEC'),...
      RUDANG(LE=9,NI=9,LO=-25,SC=6.,UN='DEGREES')
LABEL (G1) SHIP HEADING AND DESIRED HEADING VS TIME
LABEL (G1) K5=.75 X=1 IN2=0.00349
LABEL (G2) DESIRED TRAJECTORY AND
LABEL (G2) ACTUAL TRAJECTORY (Y) VS TIME
LABEL (G3) DESIRED TRAJECTORY AND
LABEL (G3) ACTUAL TRAJECTORY (X) VS TIME
LABEL (G4) RUDDER ANGLE VS TIME
END
STOP
```

LIST OF REFERENCES

1. Miguel Alvaro Marques Policarpo, Course and Station Keeping with Automatic ship Control, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1980.

2. Beser Jacques and Parkinson Bradford W., "The Application of NAVSTAR Differential GPS in the Civilian Community", Jounal of the Institute of Navigation, p.107, Vol.29, No.2, 1982.

3. Jorgensen P.S., "Navstar/Global Positioning System 18-Satellite Constellations", Journal of the Institute of Navigation, p.89, Vol.27, No.2, 1980.

4. Davidson Kenneth S.M., and Schiff Leonard I., "Turning and Course-Keeping Qualities", Transactions SNAME, p.179, Vol.54, 1946.

5. Nomoto K., Taguchi T., Honda K. and Hirano S., "On the Steerig Qualitiesof ships", Internation Shipbuilding Progress, pp.355-360, Vol.4, No.35, July 1957.

6. Koyama T., "Inprovement of Course Stability by the Subsidiary Automatic control", Internation Shipbuilding Progress, pp.126-133, Vol.19, No.212, 1972.

BIBLIOGRAPHY

Comstock,J.P., Principles of Naval Architecture, The Society of Naval Architecs and Marine Engineers,1967.

Davidson Kenneth S.M., "On the Turning and Steering of Ships", Transactions SNAME, pp.287-307,Vol.57,1949.

Schiff Leonard I.and Gimprich Marvin, "Automatic Steering of Ships by proportion control", Transactions SNAME, pp.94-118,Vol.57,1949.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5100	2
2.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
3.	Professor George J. Thaler, Code 62Tr Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943-5100	5
4.	Professor Alex Gerba Jr., Code 62Gz Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943-5100	1
5.	Department Chairman, Code 62Rr Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943-5100	1
6.	Mr George Curry HENSCHEL 9 Hoyt Drive, P.O. Box 30 Newburyport, Mass 01950	1
7.	Mr John Carter HENSCHEL 9 Hoyt Drive, P.O.Box 30 Newburyport, Mass 01950	1
8.	LT. Sommart Vimuktananda 27/40 Soi Suan luang,Klong-Tun Bangkok,10250 Thailand	3

215645

Thesis
V683
c.1

Vimuktananda
An autopilot for
course keeping and
track following.